Developing Evaluation Method of Moisture Susceptibility for Cold Mix Asphalt

By

Cheng Ling

A thesis submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
CIVIL & ENVIRONMENTAL ENGINEERING

at the
UNIVERSITY OF WISCONSIN – MADISON
2013
Executive Summary

Cold Mix Asphalt (CMA) serves as a promising alternative for a wide range of paving applications from preventative maintenance and repair, to full-scale pavement construction. Compared to traditional Hot Mix Asphalt (HMA) and Warm Mix Asphalt (WMA), CMA provides a number of benefits that make it a promising alternative to conventional paving technologies, including reduction in heating energy and longer working time for transportation and placing. However, the reported higher air void content and higher moisture susceptibility of CMA relative to traditional HMA present legitimate concerns that has limited more widespread use of CMA to date. To mitigate the potential for moisture damage in CMA, it is necessary to include a simple and effective method for evaluating moisture susceptibility in the material selection phase of the mix design process.

The most direct way to prevent moisture sensitivity is to require a minimum threshold of aggregate coating as part of CMA mix design in regards to both extent and quality of coating. This study refines a recently developed method to quantify aggregate coating extent in CMA using Digital Image Analysis Methods and applies the procedure to several aggregate-emulsion systems to isolate factors most directly affecting aggregate coating. After identifying the most significant factors, a regression analysis of the experimental results is used to develop quantitative models to predict coating of aggregates in CMA as a function of mix design parameters. Results show that not only Image Analysis Method serves as an effective and reliable tool in identifying aggregate coating, but also that the regression models developed to predict coating are sensitive to emulsion type, aggregate gradation and residual asphalt content.
Including evaluation of coating quality is a generally accepted practice in mix design for conventional HMA, WMA, and CMA. This study introduces the concept that it is necessary to assess quality of coating as a means to ensure adequate bonding between the asphalt and aggregate to truly assess potential for moisture damage. To evaluate quality of coating, a Modified Boiling Test procedure on cured CMA loose mixture that involves application of the Image Analysis Method to quantify the coating before and after boiling was developed. Results reveal that after curing is achieved as indicated by negligible moisture loss in the mixture, the bonding between emulsion residue and aggregate continues to increase with curing time. Modified Boiling Test results on fully cured CMA loose mixture indicate that CSS-1hl performs much better than CSS-1h and CSS-2 emulsion, showing the best coating quality. The results were also verified by Binder Bond Strength (BBS) test on emulsion residues and asphalt emulsions.

The relationship between coating quality and mixture performance was verified through comparison of boiling test results to mixture moisture damage as measured by the Tensile Strength Ratio (TSR). Prior to conducting this comparison a CMA mix design method was proposed to ensure a uniform process for selection of design emulsion content and preparation of mixture samples. The proposed CMA mix design method determines the design emulsion content (DEC) based on volumetric analysis and mixture indirect tensile strength. The Tensile Strength Ratio (TSR) test based on this mix design shows consistency with Modified Boiling test result and correlation between TSR test and Modified Boiling test is also established.
Acknowledgement

I would express my sincere gratitude to my committee members Professor William J. Likos and Professor James Tinjum for offering their time and suggestions on completing this thesis. I would thank my advisor, Professor Hussain U. Bahia for the lasting direction and encouragement on my study and research. I would extend my gratitude to Dr. Andrew Hanz for his academic advice on my research and thesis. I would also like to acknowledge the Asphalt Research Consortium for funding this research.

A sincere thank to my friends in Modified Asphalt Research Center who help me to accomplish this goal. I have learned a lot from all of you, either in the research or in the life. It is always fun to stay with you.

Finally I would like to thank my loved family. This work would not be possible without the lasting support from my family. Thank you.
List of Contents

Executive Summary ................................................................................................................. i
Acknowledgement .................................................................................................................. iii
List of Contents ....................................................................................................................... iv
List of Figures ......................................................................................................................... vii
List of Tables .......................................................................................................................... ix
List of Equations ..................................................................................................................... x

I. Introduction ....................................................................................................................... 1
   1. Background .................................................................................................................... 1
   2. Problem Statement ....................................................................................................... 3
   3. Research Hypothesis .................................................................................................... 4
   4. Research Objectives .................................................................................................... 4
   5. Thesis Outline .............................................................................................................. 4

II. Literature Review ............................................................................................................. 6
   1. Coating Philosophy ..................................................................................................... 6
      1.1 Wetting and Spreading .......................................................................................... 6
      1.2 Charge Compatibility ............................................................................................. 8
      1.3 Factors Influencing Aggregate Coating for CMA ............................................... 10
   2. Bonding Mechanisms ................................................................................................... 11
      2.1 Adhesion ............................................................................................................... 11
      2.2 Curing .................................................................................................................... 12
      2.3 Factors Influencing Adhesion between Asphalt and Aggregate ......................... 13
   3. Evaluation Methods of Moisture Susceptibility for Asphalt Mixture .................... 15
      3.1 Coating Test .......................................................................................................... 16
      3.2 Boiling Test ............................................................................................................ 17
      3.3 Binder Bond Strength (BBS) Test ......................................................................... 18
      3.4 Tensile Strength Ratio (TSR) Test ........................................................................ 18
   4. Mix Design Method for CMA ...................................................................................... 19
4.1 Asphalt Institute Method ................................................................. 19
4.2 Superpave Method ........................................................................... 20
4.3 Mix Design Procedure for CMA....................................................... 21

III. Introduction to Image Analysis Method on Aggregate Coating .......... 25
1. Background ...................................................................................... 25
2. Overview of Image Processing & Analysis System (iPas) ................... 26
3. Description of Image Analysis Procedures ....................................... 28
4. Case Study......................................................................................... 29

IV. Materials and Methods .................................................................... 38
1. Asphalt Emulsion and Residue Tests .............................................. 38
   1.1 Materials....................................................................................... 38
   1.2 Testing Method............................................................................... 38
2. Coating Test .................................................................................... 44
   2.1 Materials....................................................................................... 44
   2.2 Testing Method............................................................................... 48
3. Modified Boiling Test ...................................................................... 48
   3.1 Materials....................................................................................... 48
   3.2 Testing Method............................................................................... 49
4. Binder Bond Strength (BBS) Test ..................................................... 51
   4.1 Materials....................................................................................... 51
   4.2 Testing Method............................................................................... 52
5. Development of CMA Mix Design .................................................... 54
   5.1 Materials....................................................................................... 54
   5.2 Testing Method............................................................................... 56
6. TSR Test .......................................................................................... 63
   6.1 Materials....................................................................................... 63
   6.2 Testing Method............................................................................... 64

V. Results and Analysis ......................................................................... 66
1. Asphalt Emulsion and Residue Properties ...................................... 66
   1.1 Rotational Viscosity ..................................................................... 66
   1.2 Residue Recovery Test Results .................................................. 66
   1.3 PG Testing—High Temperature .................................................. 67
1.4 PG Testing—Intermediate Temperature .............................................................68
1.5 Frequency Sweep Test—Low Temperature .........................................................68
2. Coating Test Results ...............................................................................................70
  2.1 Factors Influencing Aggregate Coating ..............................................................70
  2.2 Best Subsets Regression .....................................................................................71
3. Modified Boiling Test Results .................................................................................73
  3.1 Determination of Testing Conditions for Base Gradation Aggregate ...............73
  3.2 Modified Boiling Test Results for Base Gradation Aggregate ............................75
  3.3 Determination of Testing Conditions for Single Size Aggregate .......................76
  3.4 Modified Boiling Test Results for Single Size Aggregate .................................77
4. BBS Test Results .....................................................................................................78
  4.1 Test Results on Residues ....................................................................................78
  4.2 Test Results on Emulsions ..................................................................................80
5. CMA Mix Design .....................................................................................................82
  5.1 Compaction .........................................................................................................82
  5.2 Curing ..................................................................................................................84
  5.3 Volumetric Analysis ...........................................................................................85
  5.4 Determination of Design Emulsion Content (DEC) ............................................87
6. TSR Test Results .....................................................................................................90
  6.1 Test Results with Standard Conditioning ............................................................91
  6.2 Test Results with Modified Conditioning ............................................................91
  6.3 Comparison of CR, BR and TSR .........................................................................93
VI. Findings, Conclusions and Recommendations ......................................................95
  1. Summary of Major Findings and Conclusions .....................................................95
  2. Recommendations for Future Work ......................................................................96
VII. References .............................................................................................................99
List of Figures

Figure II-1 (a) Low wettablity (b) High wettability (8) ................................................................. 7
Figure II-2 Scheme of Young’s Equation (8) .................................................................................. 8
Figure II-3 Scheme of cationic emulsion composition ................................................................. 9
Figure III-1 Intensity histogram for a grayscale image of asphalt mixture (53) ....................... 27
Figure III-2 Steps of image processing (53) .................................................................................. 28
Figure III-3 Scanner used to produce image for processing .................................................... 30
Figure III-4 Interface of ‘iPas’ .................................................................................................... 31
Figure III-5 Comparison of virtual gradations by varying ‘Hmax size’ ................................... 33
Figure III-6 Binary images with different Hmax values ............................................................. 35
Figure III-7 Binary images with different threshold values ...................................................... 36
Figure III-8 Image processing results ......................................................................................... 37
Figure III-9 Comparison between original image and binary image ....................................... 37
Figure IV-1 Rotational Viscometer ........................................................................................... 39
Figure IV-2 Dynamic Shear Rheometer ................................................................................. 42
Figure IV-3 Gradations used in Coating Test ........................................................................... 46
Figure IV-4 Boiling Test apparatus ......................................................................................... 49
Figure IV-5 Samples on silicone mats for drying ................................................................. 50
Figure IV-6 Binder Bond Strength (BBS) Test apparatus (34) .................................................. 52
Figure IV-7 Application of binder on stub and aggregate substrate (34) ................................... 53
Figure IV-8 Application of emulsion on substrate .................................................................. 54
Figure IV-9 Gradation used in CMA Mix Design ................................................................. 56
Figure IV-10 Superpave Gyratory Compactor with perforated mold ..................................... 57
Figure IV-11 CMA mixture samples with confining molds .................................................... 58
Figure IV-12 Scheme I – below SSD condition ................................................................. 60
Figure IV-13 Scheme II – equal to or above SSD condition .................................................. 61
Figure IV-14 Indirect Tension test equipment ....................................................................... 62
Figure V-1 Moisture loss within 72 hours curing at 60°C oven ................................................. 74
Figure V-2 Effect of curing time and boiling time on Coating Ratio ........................................ 75
Figure V-3 Modified Boiling Test results for base gradation aggregate ................................. 76
Figure V-4 Determination of curing condition and boiling time ............................................. 77
Figure V-5 Modified Boiling Test results for single size aggregate ......................................... 78
Figure V-6 BBS test results on emulsion residues ................................................................. 80
Figure V-7 Comparison of BBS test results on emulsions ...................................................... 81
Figure V-8 Comparison of compaction curves for CSS-1h mix ............................................... 83
Figure V-9 Moisture loss during curing for CSS-1h mix ......................................................... 84
Figure V-10 (a)-(c) Comparison of volumetric parameters for CSS-1h limestone and granite samples ........................................................................................................................................86
Figure V-11 Air voids and ITS for CSS-1h and CSS-1hl mixes ..................................................................................88
Figure V-12 Fracture surface of IDT sample ...............................................................................................................89
Figure V-13 Conditioning of CSS-1h limestone samples in water bath .................................................................91
Figure V-14 TSR results using modified conditioning .................................................................................................92
Figure V-15 Correlations between CR, BR and TSR ........................................................................................................94
List of Tables

Table II-1 Evaluation Method for Moisture Susceptibility on Loose Mixture ......................... 15
Table II-2 Evaluation Method for Moisture Susceptibility on Compacted Mixture ................ 16
Table IV-1 Summary of Superpave PG Test Used in this Study ........................................ 42
Table IV-2 Experimental Matrix for Coating Test .................................................................. 45
Table IV-3 Residual Asphalt Content Based on Duriez Method ............................................. 47
Table IV-4 Experimental Matrix for Boiling Test ................................................................... 48
Table IV-5 Experimental Matrix for BBS Test ...................................................................... 51
Table IV-6 Experimental Matrix for CMA Mix Design ........................................................ 55
Table IV-7 Experimental Matrix for TSR Test ...................................................................... 64
Table V-1 Rotational Viscosity for Emulsions of Different Storage Time ............................. 66
Table V-2 Emulsion Residue Content .................................................................................... 67
Table V-4 High Temperature True Grade for Emulsion Residues ........................................ 67
Table V-5 Low Temperature True Grade for Emulsion Residues ......................................... 68
Table V-6 Summary of PG Grade for Residue of Emulsions ................................................ 69
Table V-7 ANOVA Table for Coating Test .......................................................................... 70
Table V-8 Tukey’s Test Results for Three Most Significant Factors ..................................... 71
Table V-9 Factors Selection by Best Subset Regression ....................................................... 72
Table V-10 BBS Test Results on Emulsion Residues ............................................................ 79
Table V-11 BBS Test Results on Emulsions ......................................................................... 81
Table V-12 Locking Point during Compaction for CSS-1h mix .......................................... 83
Table V-13 Samples Dimensions Change after Curing for CSS-1h Mix ............................... 85
Table V-14 Volumetric Analysis for CSS-1h Mix ................................................................. 85
Table V-15 Superpave Specification Limits for VMA and VFA ................................................ 87
Table V-16 Design Emulsion Content for Emulsion-Aggregate Systems ......................... 90
Table V-17 Verification of Mix Design for CMA ................................................................. 90
Table V-18 TSR Results with Standard Conditioning for CSS-1h Mixes ............................. 91
Table V-19 TSR Results with Modified Conditioning ......................................................... 92
Table V-20 Summary of Test Results of Modified Boiling Test, BBS Test and TSR Test ....... 93
List of Equations

Equation II-1 .................................................................................................................. 8
Equation II-2 .................................................................................................................. 8
Equation IV-1 ................................................................................................................ 40
Equation IV-2 ................................................................................................................ 45
Equation IV-3 ................................................................................................................ 50
Equation IV-4 ................................................................................................................ 51
Equation IV-5 ................................................................................................................ 53
Equation IV-6 ................................................................................................................ 58
Equation IV-7 ................................................................................................................ 58
Equation IV-8 ................................................................................................................ 58
Equation IV-9 ................................................................................................................ 58
Equation IV-10 .............................................................................................................. 58
Equation IV-11 ............................................................................................................. 58
Equation IV-12 ............................................................................................................. 59
Equation IV-13 ............................................................................................................. 59
Equation IV-14 ............................................................................................................. 59
Equation IV-15 ............................................................................................................. 59
Equation IV-16 ............................................................................................................. 59
Equation IV-17 ............................................................................................................. 59
Equation IV-18 ............................................................................................................. 60
Equation IV-19 ............................................................................................................. 60
Equation IV-20 ............................................................................................................. 60
Equation IV-21 ............................................................................................................. 60
Equation IV-22 ............................................................................................................. 60
Equation IV-23 ............................................................................................................. 60
Equation IV-24 ............................................................................................................. 61
Equation IV-25 ............................................................................................................. 61
Equation IV-26 ............................................................................................................. 61
Equation IV-27 ............................................................................................................. 62
Equation IV-28 ............................................................................................................. 64
Equation V-1 .................................................................................................................. 71
I. Introduction

1. Background

Road pavement serves as a critical component of modern infrastructure, and due to its importance to the economy and personal mobility it has been the focus of numerous researchers focused on evaluating design methods and materials selection procedures to accommodate dramatically increasing traffic volume and loading experienced during the last few decades. Hot mix asphalt (HMA) is the most widely used construction material for flexible pavements constituting over 90% of the entire road pavements in the United States. HMA pavement provides good quality and smooth ride to the public. However, the production of HMA requires a significant amount of energy, because the mixing and compaction of HMA are required to be conducted at high temperatures typically between 135°C to 180°C. Meanwhile, the dust and contaminants from such high temperature heated aggregate and mixture also lead to considerable air pollution. Therefore, people are trying to find more environmentally friendly production methods for asphalt materials that provide a similar quality as HMA at reduced energy consumption and emissions.

Recent research efforts have focused on further development of Cold Mix Asphalt (CMA). CMA is produced with aggregate mixed with emulsified asphalt which is typically called “asphalt emulsion” instead of the hot asphalt binder. Compared to traditional Hot Mix Asphalt (HMA) and Warm Mix Asphalt (WMA), CMA offers a number of advantages that make it as an attractive alternative for a wide range of paving applications from preventative maintenance and repair, to full-scale pavement construction. Namely, CMA does not require heating the asphalt binder or full drying of the aggregate material, saving significant amounts of energy in mix production and decreasing the contaminant and dust emission. Also, CMA can be stockpiled and has a longer
working life, meaning it can be transported longer distances and placed in locations generally inaccessible or impractical for more traditional methods (1).

Despite the benefits of CMA, a number of performance-related concerns need to be addressed before CMA can be systematically applied in the field, one of which is the moisture damage in the form of stripping due to the loss of bonding between asphalt binder residue and aggregate. Moisture damage also leads to other types of pavement distresses such as rutting, fatigue cracking and raveling (2). A primary challenge associated with moisture susceptibility of CMA is the presence of water in the mixture. There are two sources of water in CMA: residual moisture in the aggregate material because it is not dried during production and the water present in the asphalt emulsion. In both instances, the water slowly evaporates over time as the mixture cures, which in turn affects the bulk mixture physical and mechanical response. As water within the binder film evaporates, the mixtures shrink with density being reduced (3). Or, if the water is entrapped between aggregates, air voids are created. As a direct result of incomplete coating, bonding and residual moisture within the mixture, the sensitivity of CMA to moisture is a critical early-life distress.

In order to address the moisture susceptibility of the CMA materials, a simple and effective evaluation method is needed to support selection of quality materials. A number of methods have been successfully used to evaluate the moisture susceptibility of asphalt mixtures (4,5,6,7) either on loose mixture or compacted mixture for HMA. Tests on loose mixture are economical and simple but they do not consider the mechanical properties of the mixtures; while tests on compacted mixtures include the mechanical properties however they are complicated, costly and time consuming (8). However, compared with HMA, very few uniform procedures or standards for CMA related to mix design or performance evaluation have been established or used in the field.
2. Problem Statement

Aggregate coating in HMA is achieved by reducing the asphalt binder viscosity with the application of heat energy and mechanical spreading during mixing. To overcome the need for heating the asphalt binder in CMA, asphalt emulsions are used. Asphalt emulsion is a heterogeneous system where asphalt particles are suspended in the water in form of small droplets under the effect of emulsifier. Asphalt emulsions exhibit a relatively low ambient temperature viscosity, allowing them to be spread over aggregates with a similar mechanical effort as HMA but without heat (9). However, since the emulsifiers and additives used to create asphalt emulsions induce a net charge (cationic or anionic) on the emulsion, surface charge compatibility with the project aggregates is a concern. The ionic compatibility between an emulsion and aggregate source affects both coating and performance as the adhesive bond between the aggregate and emulsion residue will suffer if the system is incompatible (10). Therefore, a quick and simple test on coating extent to check the charge compatibility of CMA mixture to prevent potential moisture damage is desired.

Moisture damage in HMA is realized as stripping of the asphalt film from the aggregate surface due to loss of bonding in the presence of water, which here is identified as coating quality. However, since emulsion is involved, the typical evaluation method is not applicable due to the addition of emulsifier and inclusion of a curing process to ensure the material tested in the laboratory is representative of what is placed in the field. To address these issues, it is necessary to modify existing or develop new test methods to evaluate bonding as a measure of coating quality.

Overall, various methods of moisture susceptibility evaluation developed for use in HMA cannot be applied directly to CMA. Specific aspects of CMA that need to be addressed include development of mix design and curing methods, establishing performance thresholds, and selection of tests best capable of quantifying both the extent and quality of coating. This research
serves as an advancement of the current state of practice in this area by providing a simple and effective evaluation method combining coating extent and coating quality to improve the reliability of CMA mix designs.

3. **Research Hypothesis**

The hypothesis of this research is that moisture susceptibility of Cold Mix Asphalt mixtures with various emulsions and aggregates can be evaluated and ranked through coating extent and quality.

4. **Research Objectives**

The overall goal of this research is to develop a simple and effective test method for evaluation of moisture susceptibility of CMA based on both extent and quality of coating. To meet this goal the following objectives of this study were established:

- Develop a simple and objective test for extent of coating based on digital image analysis on loose mixture samples.
- Validate the quality of coating determined by Modified Boiling Test with Binder Bond Strength Test and compacted mixture Tensile Strength Ratio Test.

5. **Thesis Outline**

This thesis is structured into five primary sections with the following contents:

Chapter I: Introduction – This chapter includes a background on CMA application and its benefits compared to HMA, as well as the potential moisture damage problem for CMA. Also the problem statement, research hypothesis and research objectives are included.

Chapter II: Literature Review – This chapter presents the coating and bonding mechanisms for CMA, followed by literature review on evaluation methods of moisture susceptibility used nowadays on asphalt mixture, and the currently developed mix design method for CMA.
Chapter III: Introduction to Image Analysis Method on Aggregate Coating – This chapter introduces the use of image analysis method on aggregate coating evaluation. Detailed analysis procedures and case study are also provided.

Chapter IV: Materials and Methods – This chapter offers a detailed description of testing materials and methods used in this research, including asphalt emulsion and residue test, coating test, modified boiling test, BBS test, mix design for CMA and TSR test.

Chapter V: Results and Analysis – This chapter includes all of the results produced by the above test methods. The coating test is used to screen the significant factors affecting aggregate coating through statistical analysis. Also, regression models for predicting aggregate coating are developed. Besides, Modified Boiling Test is applied to rank the coating quality of different cold mixes. The BBS test and TSR test are compared with the Modified Boiling Test to verify the test results.

Chapter VI: Conclusions and Recommendations – This chapter summarized all of the findings in this thesis and draw the final conclusions. Recommendations for future research are also proposed.
II. Literature Review

This chapter provides a detailed literature review to cover the fundamental principles of coating and bonding, as well as evaluation methods for moisture susceptibility for asphalt mixture and mix design method for CMA.

1. Coating Philosophy

Coating is an important variable in providing asphalt mixture moisture resistance and strength. To further investigate the factors influencing coating an understanding of the fundamental concepts of coating of CMA is necessary. Topics addressed in this section include: wetting and spreading mechanisms, emulsion charge compatibility and factors influencing CMA coating.

1.1 Wetting and Spreading

Rheology and surface chemistry are two basic sciences which help people understand coating, wetting and spreading phenomenon (11). Rheology is the study of flow of matter, mainly as liquid or solids under specific conditions in response to an applied force. In applications to coating, viscosity, defined as a measure of its resistance to gradual deformation by shear stress or tensile stress, is a critical rheological property. For viscoelastic materials such as asphalt or polymers, viscosity is strongly dependent on temperature, therefore in manufacturing or production the viscosity of the material is adjusted to reach the target consistency by controlling temperature. For coating a proper viscosity is required to both promote spreading and ensure an adequate film thickness applied to the substrate surface.

In surface chemistry, coating is controlled by both wetting and adhesion phenomena, which is strongly affected by adsorption processes (12). To understand the wetting and spreading phenomenon with surface chemistry, surface free energy serves as an important concept. Surface
free energy, also known as specific surface energy, is the amount of additional free energy to increase the unit area of surface. For isotropic materials, surface free energy is often referred to surface tension. The surface free energy is indirectly estimated through contact angle measurement with the approach presented by Zisman (13). Substrates with higher surface free energy will have a stronger tendency to adsorb materials from atmosphere such as moisture and dust, and reduce its wettability.

Wetting is the spreading and contact of a liquid over a solid substrate surface (14). Wetting is important in both coating and adhesive bonding, because both phenomena are dependent on the spreading of materials on the substrate surface. A commonly used method to determine the wettability of a liquid is to measure the contact angle (θ) of a drop of the liquid placed on the surface of the solid substrate. Contact angle of zero (θ=0°) is usually called perfect wetting and will spread spontaneously on the substrate surface. More often, partial wetting is observed with a finite contact angle as shown in Figure II-1. If contact angle is greater than 90°, it is usually called non-wetting. In this circumstance the liquid drop is not chemically compatible with the surface, thus maintaining its original shape is preferred over spreading. Therefore, a lower contact angle is preferred to create a good wetting situation.

![Figure II-1 (a) Low wettability (b) High wettability (8)](image)

Contact angle can also be related with surface free energy of the solid, liquid and solid-liquid interface by Young’s Equation (8), expressed as:
\[ \gamma_s = \gamma_{sl} + \gamma_L \cos \theta \]  \hspace{1cm} \text{(II-1)}

where \( \gamma_s \) is the solid surface energy, \( \gamma_{sl} \) is the solid-liquid interfacial energy, \( \gamma_L \) is the liquid surface energy, and \( \theta \) is contact angle (Figure II-2).

![Figure II-2 Scheme of Young’s Equation (8)](image)

Spreading coefficient is a parameter to determine if spontaneous spreading could occur in terms of surface free energy, expressed as:

\[ S_{ls} = \gamma_s - \gamma_{sl} - \gamma_L \]  \hspace{1cm} \text{(II-2)}

If \( S_{ls} > 0 \), spontaneous spreading which is favorable to coating will occur. Otherwise, wetting and spreading is difficult to achieve with low spreading property. Therefore, to encourage wetting, \( \gamma_{sl} \) and \( \gamma_L \) should be as small as possible, which can be achieved by adding surfactant (e.g. asphalt emulsifier) into the liquid to decrease the surface energy of liquid and solid-liquid interface (15). Otherwise, external energy (i.e. mixing) is needed to help wetting and spreading.

### 1.2 Charge Compatibility

Compatibility has numerous definitions in various subjects. In application to asphalt technology, compatibility mainly refers to the bonding/adhesion property between the asphalt binder and aggregate to prevent moisture susceptibility (16). However, this definition is limited to hot mix asphalt (HMA) design concept and requires additional considerations for CMA. In HMA,
compatibility is imposed during production by applying energy in the form of heat and mixing to force complete coating, thus compatibility issues are only observed as adhesion failure in-service. In contrast, no heating energy is applied to CMA as coating is achieved by mixing and chemical interactions between the surface of the aggregate and the emulsifier used in the emulsified asphalt. As a result, 100% coating is not always achieved in CMA mixture, therefore both extent of coating and quality of coating in-service must be considered. Since the emulsifiers and additives used to create asphalt emulsions induce a net charge (cationic or anionic) on the emulsion, surface charge compatibility with the project aggregates is a critical concern which affect both coating, bonding and further performance. Therefore, the compatibility discussed in this paper refers to emulsion charge compatibility instead of adhesion property.

Asphalt emulsion is a heterogeneous system where asphalt particles are suspended in the water in form of small droplets under the effect of emulsifier as shown in Figure II-3. An asphalt emulsion generally has three basic components: asphalt cement (40% to 75%), water (25% to 60%) and emulsifier agent (0.1% to 3.5%) (17). The chemistry of emulsifier agent determines the charge designation. Emulsifiers are classified into three categories depending on the charge their head groups adopted in water: anionic with negative charge, cationic with positive charge and non-ionic without charge. The properties of asphalt emulsion is largely influenced by the type and concentration of emulsifier used (17).
The aggregates used in CMA also carry a net surface charge: calcareous aggregates have a net-positive surface charge, while siliceous aggregates have net negative surface charge (18). Examples of these aggregate mineralogies commonly used in paving application are limestone and granite respectively. Conceptually, when aggregates and emulsion are combined, calcareous aggregates tend to be more charge compatible with negatively-charged anionic emulsion than positively charged cationic emulsion due to the reversely-charged attraction. As a result improved coating is achieved with calcareous aggregates when used in combination with anionic emulsion. For siliceous aggregates, cationic emulsion is more preferable than anionic considering charge compatibility. Generally, cationic emulsion is more commonly used in the industry than anionic. As reported in the literature (18), cationic emulsion performance is less sensitive to aggregate mineralogy in the field relative to anionic emulsion.

1.3 Factors Influencing Aggregate Coating for CMA

A number of factors affect aggregate coating for CMA including aggregate-asphalt surface charge, free moisture existing in the aggregate before mixing, temperature of materials, and aggregate surface texture (18).

As discussed previously, surface charge compatibility is very important in aggregate coating for CMA particularly for anionic emulsion, because emulsion-aggregate with compatible charge would provide a stronger ionic attraction resulting in improved coating and bonding.

The amount of coating achieve also depends on the amount of pre-mixing water added into aggregate prior to mixing with emulsion (18). In current practice, the optimum pre-mixing water content for coating is determined by trial and error in which mixtures are prepared at different water contents and coating is evaluated by visual observation after combining the wet aggregate and emulsion. Cationic and anionic emulsion behaves differently in pre-mixing water content in
coating. Generally cationic emulsion needs to add more water to ensure good mixing and coating (18).

Some aggregates were also found to be temperature sensitive for coating; therefore success of CMA could depend on ambient conditions during production (18). For these aggregates, higher temperature is preferable for better coating. Mixing time is also important as insufficient mixing could lead to inadequate coating, while long mixing times potentially lead to early stripping. In addition to the factors previously stated, mix design and materials properties such as dust coatings on the aggregate surface, absorption of aggregate, aggregate gradation, filler content, emulsion viscosity, and emulsion breaking rate (formulation) all influence coating ability.

2. Bonding Mechanisms

Bonding between aggregate and asphalt mainly has two components: cohesive bonding within asphalt binder, and adhesive bonding on the interface between aggregate and asphalt. Asphalt binder cohesive strength is an inherent material property and is thus mainly dependent on the physical properties of the asphalt binder, such as stiffness. However, adhesion is a more complicated mechanism of bonding because two different materials are involved and their interaction needs to be understood. In applications to CMA, time also affects the quality of bonding as the properties of the asphalt binder used to coat the aggregate change with time due to curing.

2.1 Adhesion

In ASTM D907, adhesion is defined as “the state in which two surfaces are held together by interfacial forces which consist of valence forces, interlocking forces or a combination of both.” Adhesion determines the tendency of two different materials molecules to adhere to each other (8). Different mechanisms may occur simultaneously to generate adhesion. The most commonly used theories used to explain the mechanisms of adhesion are mechanical theory, chemical theory,
weak boundary theory, and thermodynamic theory (19,20). These theories are briefly described below.

- Mechanical theory assumes mechanical interlock occurs when asphalt is forced into aggregate pores along the rough surface of aggregate, which provides more mechanical interlock and good adhesion;

- Chemical theory suggests that adhesion mainly depends on chemical compositions of both asphalt and aggregate;

- Weak boundary theory indicates that rupture always occur at the weakest link of asphalt-aggregate interface;

- Thermodynamic theory considers adhesion to be a thermodynamic phenomenon related to surface energy exchange between asphalt and aggregate.

All these theories and mechanisms are not independent with each other, and researchers have agreed that several mechanisms of adhesion occur simultaneously in asphalt mixture (8).

2.2 Curing

In paving applications curing is most commonly used in the area of concrete material, referring to the hardening of concrete with time due to the hydration reaction between the cement paste and water. The rate of this reaction and ultimate strength depend on the environmental conditions used during curing, and optimum conditions are warm temperatures and high humidity. Based on this concept, curing is defined as the maintaining of a satisfactory moisture content and temperature in concrete for a period of time immediately following placing and finishing so that the desired properties may develop (21). In applications to CMA, curing is similar to the definition used for concrete in that it refers to the evolution of performance properties with time for a given set of environmental conditions. Also similar to concrete the rate of strength gain
depends on environmental conditions. However, for CMA curing refers to the physical process of moisture evaporating from the mixture as the process of hydration and other chemical reactions that occur during curing of concrete are not present in CMA. Given that water is present in the mix from both the emulsion and moisture entrapped in the aggregate, the properties of cold mixes evolve with time especially in early life. The formation of bonding for cold mixes occurs with the increasing time and evaporation of the water, which is defined as curing of CMA. Curing process is a distinctive property for CMA that does not occur in HMA and WMA, because these materials are produced with conventional asphalt and at temperatures well above 100°C, therefore very little moisture is present in the mix and thus they usually reach their mature state and gain most of strength within a very short period after construction.

In addition to environmental conditions and curing time, the curing of CMA is influenced by many other factors including: initial moisture content including pre-mixing aggregate moisture and water in emulsion, air voids/permeability of compacted mixture, absorption of aggregate, and breaking rate of the emulsion. Effects of most materials-related factors can be overcome by adjusting curing temperature or time, thus these factors were deemed most critical (22).

2.3 Factors Influencing Adhesion between Asphalt and Aggregate

As discussed previously, curing is an important factor that influences adhesion between asphalt and aggregate as the properties of the asphalt are continuously changing. In addition to curing, materials-related factors affecting the adhesion between asphalt and aggregate include: interfacial tension between asphalt and aggregate, chemical composition of asphalt and aggregate, asphalt binder viscosity, surface texture of aggregate, aggregate porosity, aggregate cleanliness, and aggregate temperature and moisture content while mixing (23). Most of these factors are classified as individual material properties or asphalt-aggregate interactions.
Factors that influence the adhesive strength of asphalt to an aggregate substrate and internal binder cohesion include: the chemical properties (e.g. polarity and composition), viscosity, film thickness, and surface energy. Previous research demonstrates that carboxylic acids in asphalt binders which are polar adhere strongly to dry aggregate, but tend to be removed easily from aggregate in the presence of water (24). This indicates the chemical interaction between asphalt and aggregate is critical in understanding the moisture resistance property. It is also found that asphalt with high viscosity tends to resist moisture better than that with low viscosity, because high asphalt binder viscosity is generally associated with asphalt binder sources that carry a high concentration of polar functional groups which promote increased bonding with the aggregate and thus more resistance to moisture damage (5). It is also reported that thicker asphalt film tends to have cohesive failure after moisture conditioning while thinner film will have adhesive failure (19). In regards to thermodynamic properties, low asphalt binder surface energy is preferable to provide better wetting of the aggregate surface (8).

The adhesive strength of the bond at the asphalt/aggregate interface is influenced by both asphalt binder and aggregate properties. Specific aggregate properties that affect adhesion include: angularity, porosity, surface area, chemistry, and surface charge (10). Related to surface charge, various mineral component of aggregate shows different affinity for asphalt. Aggregate are commonly classified as either hydrophilic which has better affinity with water than asphalt, or hydrophobic which shows greater affinity with asphalt than water (6,10,19). For example, limestone is typically considered as hydrophobic while granite is hydrophilic. Regarding physical properties, rough surface texture and high absorption are preferable for better adhesion, while moisture and dust on aggregate surface are detrimental to the adhesion of asphalt-aggregate system (8). Similar to coating, a significant factor that impacts the quality of bonding for CMA is surface charge compatibility between emulsion and aggregate (18).
3. Evaluation Methods of Moisture Susceptibility for Asphalt Mixture

Numerous test methods have been developed and evaluated for assessing asphalt mixture moisture susceptibility over the past few decades. However, given all this effort there has yet to be a test method that is generally accepted as a reliable method that is related to performance. The most common method is the indirect tension test, which is used in the mix design process to assess asphalt/aggregate compatibility. Furthermore, a majority of test methods were developed for use in HMA, while application of these methods to CMA is limited, and currently no CMA-specific methods exist.

The evaluation methods commonly used to assess moisture susceptibility are classified into two categories: tests on loose mixtures and tests on compacted mixtures (8), and commonly used tests are summarized in Table II-1 and Table II-2 respectively by previous researchers (8,37).

Table II-1 Evaluation Method for Moisture Susceptibility on Loose Mixture

<table>
<thead>
<tr>
<th>Test</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film Stripping</td>
<td>California Test 302</td>
</tr>
<tr>
<td>Static Immersion</td>
<td>AASHTO T182</td>
</tr>
<tr>
<td>Dynamic Immersion</td>
<td>Literature “Moisture Damage of Asphalt Pavement” (38)</td>
</tr>
<tr>
<td>Chemical Immersion</td>
<td>Standard Method TMH1 (Road Research Laboratory 1986, England)</td>
</tr>
<tr>
<td>Surface Reaction</td>
<td>Ford et al. 1974</td>
</tr>
<tr>
<td>Quick Bottle</td>
<td>Virginia Highway and Transportation Research Council (Maupin 1980)</td>
</tr>
<tr>
<td>Boiling</td>
<td>ASTM D3625, Tex 530-C Kennedy et al. 1984</td>
</tr>
<tr>
<td>Rolling Bottle</td>
<td>Isacsson and Jorgensen, Sweden, 1987</td>
</tr>
<tr>
<td>Net Adsorption</td>
<td>SHRP A-341 (Curtis et al. 1993)</td>
</tr>
<tr>
<td>Surface Energy</td>
<td>Thelen 1958, HRB Bulletin 192, Cheng et al., AAPT 2002</td>
</tr>
<tr>
<td>Pneumatic Pull-off</td>
<td>Youtcheff and Aurilio (1997), Meng 2010, Moraes et al. 2010</td>
</tr>
</tbody>
</table>
### Table II-2 Evaluation Method for Moisture Susceptibility on Compacted Mixture

<table>
<thead>
<tr>
<th>Test</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture Vapor Susceptibility</td>
<td>California Test 307 developed in late 1940s</td>
</tr>
<tr>
<td>Immersion–Compression</td>
<td>ASTM D1075, AASHTO T165, ASTM STP 252 (Goode 1959)</td>
</tr>
<tr>
<td>Marshal Immersion</td>
<td>Stuart 1986</td>
</tr>
<tr>
<td>Freeze–Thaw Pedestal Test</td>
<td>Kennedy et al. 1982</td>
</tr>
<tr>
<td>Original Lottman Indirect Tension</td>
<td>NCHRP Report 246 (Lottman 1982), Transportation Research Record 515 (1974)</td>
</tr>
<tr>
<td>Modified Lottman Indirect Tension</td>
<td>AASHTO T283, NCHRP Report 274 (Tunnicliff and Root 1984), Tex 531-C</td>
</tr>
<tr>
<td>Hamburg Wheel Tracking</td>
<td>Aschenbrener and Currier 1993, Tex-242-F 2009</td>
</tr>
<tr>
<td>Asphalt Pavement Analyzer</td>
<td>AASHTO TP63</td>
</tr>
<tr>
<td>Environmental Conditioning System/Simple Performance Tests</td>
<td>AASHTO TP34, NCHRP 9-34 2002-03</td>
</tr>
</tbody>
</table>

Both of two types of tests have their own pros and cons. Tests on loss mixture are economical and simple but they don’t consider the mechanical properties under specific traffic volume. On the other side, tests on compacted mixture include the mechanical properties, however they can be too complicated, costly and time consuming. Some of these tests will be presented and discussed in details below.

#### 3.1 Coating Test

Coating of HMA is addressed in production by adding heat and mixing energy to achieve close to full coating, however previous research indicates that there is a higher risk of insufficient coating with CMA (18). To ensure sufficient coating of the aggregate surface a simple and quick coating test is needed in the materials selection process. Numerous qualitative coating test procedures for evaluation of after mixing to evaluate coating based on a rating system or as an approximate percentage (18,25). All these procedures are inadequate because outputs are based
on visual observations and are thus subjective. As a result, outputs of the coating test become confounded with judgments of different operators. Researchers have also tried to use image analysis methods as a simple and quantitative tool in evaluating coating successfully in recent studies (3).

3.2 Boiling Test

The boiling test is well established as a simple and effective method to evaluate moisture susceptibility on loose mixture (26). With this test method the adhesion quality is determined based on the remaining percentage of coated area by visual observation (27). In applications to HMA, coating is assessed only after boiling to evaluate moisture sensitivity because in most cases the material is fully coated prior to conditioning. Modifications to the standard practice are required on coating evaluation for CMA before and after boiling due to the increased potential that CMA will not achieve full coating during production. As an output this test evaluates stripping through use of coating loss. Another deficiency of the current standard is that the coating is assessed visually; therefore results are not evaluated using an objective and quantitative measure. For this test to be a viable alternative an effective and objective method for quantifying coating is required.

Recent research presented various methods to quantify both the coating and coating loss during the boiling test. Specifically, the three methods evaluated include the absorption method, the mass loss method, and image analysis. The absorption method (28) seems to be a representatively quantitative method, from which the extent of coating is estimated based on the ratio of the water absorption of the mixture to the absorption of the bare aggregate. However, it is mainly applicable to aggregate with high absorption and the procedure is difficult to control. Mass Loss method has also been used (29,30) where the mass loss of the mixture before and after boiling were recorded for comparison of stripping. However the mass loss is neither significant nor easy to measure. Compared to the above methods, imaging method which quantifies the
coating extent before and after boiling provides a simple, repeatable, and intuitive method of analysis, capable of both quantifying coating and demonstrating sensitivity to the effects of boiling on coating quality (31,32). This method will be discussed in detail in subsequent sections.

3.3 Binder Bond Strength (BBS) Test

The boiling test represents an indirect method to measure quality of coating through use of an extreme conditioning step. Direct measurement of the bond at the asphalt aggregate interface using the Binder Bond Strength Test (BBS) serves as a complement to the boiling type. Previous research indicates that the bond strength relates well to the moisture damage resistance of mixtures (8). The Binder Bond Strength test, developed based on the Pneumatic Adhesion Tensile Testing Instrument (PATTI) test which has been standardized and well known in coatings and adhesives industry (33,8,36), recently serves as a procedure for measuring the effect of water conditioning on degradation of the bond at the asphalt/aggregate interface (8). Furthermore, research and guidance in AASHTO TP-91 indicates that BBS test can be applied to hot asphalt binder, emulsion residue, and partially cured emulsions, to date the BBS test has been used to characterize emulsions for chip seals (34,35).

3.4 Tensile Strength Ratio (TSR) Test

AASHTO Standard Method of Test T283 (36) “Resistance of Compacted Bituminous Mixture to Moisture Induced Damage” is one of the most commonly used procedures for determining moisture susceptibility for compacted mixture, which is also called Modified Lottman Indirect Tension Test. The test procedures include testing of unconditioned and moisture conditioned samples to assess the impacts of water on indirect tensile strength. Dry samples are compacted to 7% air voids, conditioned in a 25°C water bath for 2 hour to reach the required testing temperature, and tested. Moisture conditioned samples are compacted to the same density, subjected to vacuum saturation to a target threshold, then conditioned using an optional freeze thaw cycle and/or submersion in a water bath of 60°C for 24 hours. After conditioning the sample
is submerged in a 25°C water bath of for 2 hours to bring the conditioned samples to the required test temperature. The output of the test is the tensile strength ratio (TSR), defined as the ratio of wet to dry indirect tensile strength. Based on empirical correlations to observations in the field and the need to include moisture damage resistance in mix design, the TSR was adopted by the Superpave system as a critical parameter in mix design (37). The ASTM D4867 standard introduces the similar procedure with AASHTO T283 with a few differences in curing of loose mixture and saturation degree for the mixture (38).

4. Mix Design Method for CMA

Mix design procedures for HMA are well established and have evolved significantly with development in technology. Three design methods are available: the Hveem Method, Marshall Method, and Superpave Method (39). The mix design method used depends on the technology available to the agency and agency preference; the most common mix design method in the United States is Superpave. Relative to HMA, the development of mix design methods for CMA is significantly behind as no widely accepted mix design for CMA exists and most of the methods used by different agencies worldwide are empirical, based on field experience and limited simple lab testing. Numerous agencies and industry have developed their own detailed methods including Chevron, the U.S. Forest Service, California Department of Transportation, the Asphalt Institute, and others (18). Most of these procedures are following the similar procedure as HMA, which do not necessarily result in optimized selection of materials properties and proportions of materials due to the differences between HMA and CMA. Therefore, there is a significant research need to develop a reliable and practical mix design method for CMA to further promote use of the technology. A summary of current methods is provided below.

4.1 Asphalt Institute Method

The Asphalt Institute (AI) Method is widely used for CMA mix design all over the world. The AI Method provides guidance for design using two different compaction methods, the
Hveem compactor and Marshall compactor. Regardless of the compactor used the AI Method consists of the following general steps: (40,41,3):

1. Materials selection
2. Determination of initial emulsion content
3. Determination of optimum moisture content for coating
4. Compaction at different emulsion contents
5. Determination of optimum moisture content based on density
6. Curing
7. Determination of optimum emulsion content

While the method is successful in providing a logical process for optimizing fluids content it does not include a target density and volumetric properties or performance related criteria. Therefore, the optimum fluids contents are determined empirically. As a result previous research indicates that the performance of laboratory designed mixes does not correlate well with the field (42).

4.2 Superpave Method

Due to the limitations of AI method, researchers and practitioners moved away from this empirical method and towards a performance based mix design method—Superpave developed by SHRP. In this mix design method the compaction device used is the Superpave Gyratory Compactor (SGC) as a replacement of the Hveem Kneading Compactor or Marshall Hammer to better simulates the compaction process in the field. While the mix design method was initially developed for HMA, ASTM Standard D7229 offers detailed guidelines for preparing and compacting samples of CMA (47). The standard gyratory setting of vertical pressure of 600kPa and gyratory angle of 1.25° are adopted, and 33±5 gyrations are recommended in this standard. After compaction 20 hours of curing at ambient temperature is specified before measuring the
density. However, no target density or volumetric parameters are specified, thus guidance for determination for optimum emulsion content is lacking.

Subsequent research focused on development of a more effective and reliable mix design method for CMA that leveraged use of Superpave technology and concepts continued. Hemsley (43) used perforated gyratory molds to allow for water drainage during compaction, and compacted samples to 200 gyrations to identify the locking point. The locking point is defined as the number of gyrations at which no significant change of sample height appears after three consecutive gyrations (3), and is used as a measure of mixture workability. In the study, a workable mix was defined as a mix with a locking point less than 30 gyrations. A mix that is “harsh” or difficult to compact was defined as a mix with a locking point greater than 70 gyrations. Leseur (44) tried to compact the mixture to the onset of water drainage using perforated molds based on assumption that the density achieved in lab at the drainage point is similar to what is achieved in the field during compaction. However, due to the complexity of CMA mixture including chemical interaction between the emulsion and aggregate and development of pore pressure during compaction, most attempts in developing a mix design procedure to date have been unsuccessful, and as a result there is no generally accepted mix design method either in research or in field application.

4.3 Mix Design Procedure for CMA

Mix design for CMA from most of methods is mainly composed of determining the following items: charge compatibility of emulsion-aggregate system (coating), optimum moisture content at compaction, optimum residual asphalt content and structure performance (18). It is necessary to examined coating as part of the materials selection process to prevent moisture damage as discussed previously. Current research suggests a minimum threshold of 90% coating for surface courses (45). Results of trial compactions found that both moisture content and residual asphalt content have significant effects on density, rate of curing and performance (18).
In these studies (18,22,25) optimum fluids contents were determined through use of a simple performance measure such as Marshall Stability or similar methods.

The mix design procedure for CMA (18) commonly consists of several steps including: coating evaluation, mixing and compaction, curing, volumetric analysis and performance testing. In these procedures optimum emulsion content is determined through volumetric analysis or based on mixture performance test results. The components of the CMA mix design procedure, associated research, and future needs are discussed below:

1. Coating: A measure of coating is required to evaluate charge compatibility between emulsion and aggregate as discussed previously. If required coating is achieved, the materials are deemed compatible and the design can proceed to mixing and compaction of trial blends.

2. Compaction:
   a. Design Targets for Density and Volumetric Properties: Evaluation of trial blends for selection of optimum fluids contents requires definition of required density and volumetric property limits. In the Superpave design method, the optimum asphalt content for HMA is determined by mixture with target air voids of 4%. However for CMA, since much moisture is involved, it is neither easy nor necessary to compact to such low air voids. It is reported that the air voids of most CMA pavement is much higher than HMA after compaction in the field and keep decreasing after opening to traffic, and will be stable between 10%-15% in medium term (22,45).
   b. Method of Compaction: Numerous compaction methods were studied and compared. The Superpave Gyratory Compactor was deemed as the most practical and effective compaction method. Previous studies attempted to reduce design compactive effort relative to what is used for HMA to better simulate and compaction process in the field (46,47). Various compaction criteria were used in previous studies, such as compacting to
50 percent of total moisture evaporation, maximum gyration number, locking point, and onset of water drainage (22,48,49).

3. Curing: Curing is a distinctive process for CMA compared with HMA, because the density and mechanical properties will alter with moisture loss at different curing states. Proper curing conditions are required for the mixture to gain mechanical properties with time. Studies show that either increasing the temperature or decreasing the humidity can help accelerate curing process (22). OPTEL report (22) compared different curing conditions and proposed the most appropriate curing method—accelerated curing of 14 days at 35°C and 20% humidity, which corresponds to the cured state of CMA pavement after 2-3 years service (50).

4. Volumetric Analysis: After curing, the bulk specific gravity \( (G_{mb}) \) and theoretical maximum specific gravity \( (G_{mm}) \) are measured following the same procedure as HMA to determine the air voids. However, it’s impossible to remove all moisture in the mixture after curing either in the lab or in the field. Since water may still exist inside the sample, the volumetric analysis procedure to calculate other volumetric parameters such as voids in the mineral aggregate (VMA) and voids filled with asphalt (VFA) for HMA is not applicable for CMA due to the water remaining. Therefore a new or modified analysis procedure is needed to obtain the all volumetric parameters.

5. Performance Evaluation: Performance tests for CMA mixture are required to evaluate mechanical properties after curing. Typical performance test used for CMA includes compressive strength test under immersion, rutting resistance test, and stiffness modulus test (45). The indirect tensile strength (ITS) as measured by Indirect Tension Test (IDT) also serves as an effective tool in evaluating the relative quality of asphalt mixture and estimating the rutting and cracking potential (51). There is also potential to apply advanced test methods
developed for HMA such as flow number (FN), dynamic modulus (E*), and Thermal
Restrained Specimen Test (TSRST) to CMA to compare performance properties to HMA.
Many of these tests are used in current mechanistic pavement design methods, given the
properties of CMA after curing it is expected that these tests are also applicable to CMA,
however limited research data exists at this time.

The optimum emulsion content is then determined based on volumetric analysis and
performance tests. As previously stated, there is currently no consensus on what criteria should
be used for determination of optimum emulsion content.
III. Introduction to Image Analysis Method on Aggregate Coating

1. Background

Full aggregate coating is required in production of hot mix asphalt to prevent potential moisture damage, for HMA coating is achieved through selection of a mixing temperature that allows for a range of asphalt binder viscosity suitable to coat the aggregate. In cold mix asphalt coating is achieved through chemical compatibility between the emulsion and aggregate, as a result higher risk of insufficient coating exists in cold mix asphalt because thermal energy is not used to promote creation of sufficient bonding (18). In current practice the quality of coating achieved during mixing is evaluated using the boiling test as specified in ASTM D3625. In this test potential for stripping is evaluated by comparing aggregate coating before and after boiling based on qualitative visual observation. This study aimed to improve standard methods for evaluating coating extent and quality by introducing a quantitative method for coating evaluation and defining a parameter for coating quality based on the difference in coating observed before and after boiling.

Numerous qualitative methods are available for evaluation of coating. Standard AASHTO T195 and ASTM D2489 specify the estimation of coating for hot mix asphalt by using visual counting. ASTM D6998 also designates the evaluation method for CMA by visual judgment. Visual observation is also used as the output of the standard boiling test as specified in ASTM D3625. In application to this study these procedures were deemed inadequate because the evaluation of coating are based on visual inspection and are thus subjective and operator-dependent.
Significant efforts have been made by various researchers to provide an objective method to quantify aggregate coating. Cuciniello (75) improved the visual inspection method by adopting a criterion describing the scale of degree of coating as the reference and proposed an index as the degree of coating. Pinto et al. (32) and Swiertz et al. (3) attempted to estimate aggregate coating with image analysis of photographs taken for the mixture using a digital camera, thus presenting a promising technique for removing the subjectivity from coating evaluation.

This study continued the use of image analysis method and utilized the image processing software ‘iPas’ to evaluate aggregate coating using images obtained after mixing and after boiling. For digital image processing, the images of the mixture are converted into binary (black and white) images and individual pixels are identified as coated or uncoated based on the pixel intensity. In this method, white pixels are defined as exposed aggregate and black pixels are defined as coated aggregate. To mitigate the subjectivity and eliminate the ambient lighting interference, all images were produced with a standard office scanner in a covered environment instead of using images captured by a digital camera.

2. Overview of Image Processing & Analysis System (iPas)

Image Processing & Analysis System (iPas) is a 2-D image processing software developed by Coenen (52) and Sefidmazgi (53) to quantify the internal features of compacted asphalt mixture. The functions of the software are divided into image processing and microstructure analysis. The image processing function of the software was utilized in this study to identify aggregate coating. The concepts of image processing are introduced in this section. More details about development of ‘iPas’ and improved edition ‘iPas 2’ can be found in Coenen (52) and Sefidmazgi (53).

To obtain the image of asphalt mixture, the compacted mixture sample is cut into three sections and each section is scanned by a standard office scanner. The scanned digital image is a
RGB (Red-Green-Blue) image which shows respective intensity of each color at each individual pixel. In ‘iPas’, the image is first converted to a gray scale image to differentiate the aggregate phase and mastic and voids phase. Then the gray scale image is converted to a binary image for microstructure analysis by selecting a threshold value. Various image filtering processes are conducted to enhance the image quality for separating different phases of materials from each other, including ‘Median Filtering’, ‘Regional Maxima (Hmax) Filtering’, ‘Watershed Filtering’ and ‘Threshold Filtering’ (52,53).

![Intensity histogram for a grayscale image of asphalt mixture](image)

**Figure III-1 Intensity histogram for a grayscale image of asphalt mixture (53)**

To separate the material phases, a threshold is selected through ‘Threshold Filtering’ which is considered as the most important step in the image processing. A typical intensity histogram for a grayscale image is shown in Figure III-1. As seen from the figure, there is a threshold value at which pixels with higher intensity are considered as aggregate and pixels with lower intensity are assumed to be voids or mastic. By selecting the threshold value, the grayscale image can be converted to a binary image, in which the aggregates are shown as white while the air void and mastic in the mix is shown as black. An example of the steps of image processing is presented in Figure III-2.
After image processing, two parameters are compared with the real parameters for asphalt mixture to verify if the 2-D processed image is representative of the real condition: aggregate volume fraction and gradation (53). Once a representative binary image is determined, microstructure analysis is performed based on the image.

3. Description of Image Analysis Procedures

This study leverages of the image processing function of ‘iPas’ to obtain the extent of aggregate coating. Given that coating evaluation is conducted on loose mix rather than compacted mixtures the procedure previously described was modified slightly for coating evaluation. The image processing for determination of aggregate coating includes two steps: selection of thresholds based on bare aggregates and the application of threshold on loose mix. The analysis procedures are described in details as follows. The full procedure was also summarized in draft AASHTO format and submitted to FHWA for consideration as a provisional test method.

The validity of the coating procedure is based on selection of the threshold pixel intensity that represents the color of the aggregate, as this represents uncoated or bare aggregate in the
mixture. The correct pixel intensity is dependent on the color of the aggregate used in the mixture so the first step was to conduct image processing on the bare aggregate to define the pixel intensity that corresponds to the aggregate color. The bare aggregates of around 200g are scanned using a standard office scanner. The scanned image is loaded into ‘iPas’, and the resolution determined by the scanner used is entered. Then the image is cropped to obtain the representative image of aggregates. Gradation for the aggregate is also entered.

Image thresholding is conducted using a trial and error process to define representative pixel intensity thresholds. The threshold selection process is self-calibrating as the virtual gradation of the image is compared to the actual gradation of the sample. The threshold values are deemed correct if the shape of the gradation curve of the image matches that of the actual gradation. The output of this process is the pixel intensity value associated with the bare aggregate. For a given aggregate source, the thresholds are maintained throughout all of the analysis.

Given definition of the aggregate pixel intensity threshold the loose mix CMA is prepared and scanned. The loose mix image is processed using a procedure similar to what was discussed previously with the aggregate pixel intensity input based on the value determined for the bare aggregate. Once the image is processed, uncoated aggregate particles are differentiated from coated particles using the bare aggregate pixel intensity threshold. The extent of coating is defined as ratio of coated area to total area in the mixture.

4. Case Study

A case study in determining the coating extent of CMA loose mix prepared with anionic emulsion and limestone is presented as an example. The detailed procedures are listed as follows:

**Step 1:** Preparation of bare aggregates. Prepare 200g of bare aggregate with prescribed gradation. Add pre-mix water to be representative of field condition if necessary for CMA. After
mixing, spread the aggregates on scanner so that none of them have contact with each other to facilitate the filtering. Use of coarse aggregates is preferred.

**Step 2:** Scanning of bare aggregates. Scan the aggregate using a cardboard frame and standard office scanner as shown in Figure III-3.

![Scanner used to produce image for processing](image)

**Figure III-3 Scanner used to produce image for processing**

**Step 3:** Image loading. Open ‘iPas’ software (shown in Figure III-4) and load the scanned image into the software.
Step 4: Parameters input. Enter resolution, crop image and enter specimen properties (i.e. gradation) following the tutorial guide of ‘iPas’ (54). In this case, the resolution of the scanner is 300 ppi. Therefore the resolution entered should be 25.4/300=0.0846667 mm/pixel.

Step 5: Selection of threshold parameters. ‘Med Filt Size’ is recommended using default value of 5, while ‘Hmax Size’ and ‘Threshold’ are adjusted to obtain the optimum thresholds. ‘Min. Ag. Sz.’ should be at least 1.18 mm here (54), which means aggregates with size less than 1.18 mm are not included in analysis of the image. This selection is based on the resolution of the scanner. Using this setting aggregates with size larger than 1.18 mm are only included in this case for scanning and analyzing.

Step 5(a): Determination of “Hmax” value. To start the trial and error process of filtering select a threshold filter of 60 and Hmax filter of 40. Hold the threshold filter constant and vary the ‘Hmax’ value in increments of 20. The virtual gradations with these filtering settings are shown in Figure III-5.
(a) $H_{\text{max}}=40$

(b) $H_{\text{max}}=60$
Figure III-5 Comparison of virtual gradations by varying ‘Hmax size’

Since aggregates with size less than 1.18 mm are not included in the image analysis, there is a downward shift between the virtual gradation and actual gradation of the mix. In comparing the virtual and actual gradations the correct Hmax filter is selected based on the requirement that the virtual gradation curve is parallel to that of the actual gradation. For this example the condition of parallel gradation curves is met for a Hmax value of 60, as shown in Figure III-5.

The Hmax filter setting is further refined by visual inspection of the filtered images compared to the original image to ensure that aggregate particles are correctly identified. This step is taken to ensure that there is differentiation between aggregate shapes and that individual aggregates are not conglomerated due to use of incorrect threshold values. To conduct this comparison different areas on the image are selected and compared at smaller increments of Hmax filtering. In this example the Hmax filter range of 50 to 70 was selected as most representative of the actual gradation; therefore the Hmax filter was varied from 50 to 70 in
increments of 5. Example data is provided in Figure III-6 with selected area for inspection. Using this process the optimum ‘Hmax’ is determined as 55 as the binary image of Hmax value of 55 identify the individual aggregate shape most representatively.
Step 5(b): Determination of “Threshold” value. The selected value of Hmax is then fixed and the threshold value is varied using a similar procedure. Specifically, the virtual and actual gradation curves are still required to be parallel and the individual shapes (as opposed to agglomerations) of the aggregate need to be maintained. For this example, the threshold was varied from 40 to 80 in increments of 20. Results are presented in Figure III-7. Finally the optimum ‘Threshold’ was determined as 60, as much noise appears when threshold is set to 40 and some particles are missed at threshold of 80 as shown in the selected area in Figure III-7.
Figure III-7 Binary images with different threshold values

**Step 6:** Preparation and scanning of loose mixture. Prepare the aggregates of 3000 g with prescribed gradation, and mix with pre-mix water and emulsion. A higher quantity of material is used for preparation of CMA samples to minimize the effect of air voids and be more representative of coating experienced in full-size mixtures.

**Step 7:** Image processing. Load the image into software and enter the threshold parameters determined in Step 5. By applying filtering, the output of the uncoated percentage is 39% as shown in Figure III-8. Therefore the coating extent is 100% - 39% = 61%. Identification of individual aggregates is also required by comparing original image and binary image to verify that the binary image is representative of the actual mix; the original image and processed image are presented in Figure III-9. Note that for each aggregate or mix sample, at least three scanned image replicates are required.
Figure III-8 Image processing results

(a) Original image  
(b) Binary image

Figure III-9 Comparison between original image and binary image
IV. Materials and Methods

This chapter will provide a detailed description of experimental materials selected and testing matrix to be conducted, for emulsion and residue property test, coating test, modified boiling test, BBS test, CMA mix design and TSR test.

1. Asphalt Emulsion and Residue Tests

1.1 Materials

Four different types of emulsion were used in this research: AE-150, CSS-1h, CSS-2 and CSS-1hl. AE-150 is a typically used anionic emulsion with negatively charged emulsifier. CSS-1h, CSS-2 and CSS-1hl belong to cationic emulsion with positive charge. Based on emulsion nomenclature (9), CSS-1h is a cationic, slow setting, low viscosity, hard residue emulsion, while CSS-2 is a cationic, slow setting, high viscosity emulsion. The major difference between CSS-1h and CSS-2 is based on viscosity however there is potential that the differences also exist in the residue properties. CSS-1hl is a latex modified CSS-1h emulsion. The use of “slow-setting” emulsions is common for CMA application due to the high surface area of aggregates used in the mix design; the slow set time prevents early breaking of emulsion during mixing and transportation to ensure the mix maintains workability until it is placed in the field.

1.2 Testing Method

To evaluate the storage stability of emulsion with time and to obtain its physical properties, various tests on both emulsion and recovered residue were conducted including: viscosity, recovery, PG high temperature, PG intermediate temperature, and a DSR frequency sweep test to estimate PG low temperature properties.
Viscosity

ASTM Standard D 7496 (55) specifies the test method for measuring viscosity of emulsified asphalt by Saybolt Furol Viscometer. However, recent research suggests that this procedure is not technically sound because the shear rate that the material is subjected to varies throughout the test (62). Asphalt emulsions and conventional binders have proven to be shear sensitive, thus it is required to control shear rate to obtain an accurate measure of material consistency (viscosity). To address this issue the Brookfield Rotational Viscometer (RV) specified by Superpave for hot asphalt binder is adopted instead to measure the viscosity of different emulsions, as shown in Figure IV-1.

![Rotational Viscometer](http://www.pavementinteractive.org/article/rotational-viscometer/)

Figure IV-1 Rotational Viscometer

The RV test measures the torque required to maintain a constant rotational speed (5 RPM) of a cylinder spindle when submerged in tube filled with asphalt binder at a specified temperature. The lower rotational speed (5 RPM) selected in this study relative to ASTM standard for HMA (20 RPM) is to check the storage stability of emulsion and prevent early breaking of emulsion at high speed of rotation. Then the torque is calculated and converted to a viscosity value, this
conversion is done automatically by software embedded in the RV control system. In application to HMA ASTM D 4402 (56) specifies testing of viscosity for asphalt binder at the typical temperatures of production ranging from 135°C-150°C. Given that emulsions used for CMA are mostly stored and applied at ambient temperatures, a test temperature of 25°C was selected to evaluate the materials used in this study. Other than the change in test temperature, guidance provided in ASTM D 4402 was adopted in this study to test emulsion viscosity. The RV temperature chamber was allowed to equilibrate to 25°C. After the equilibration time a cylinder tube containing 8g of emulsion was inserted into the RV chamber. The spindle was then lowered into the sample and the system was allowed to equilibrate at the test temperature for 20 minutes. For evaluation of emulsions the No. 21 spindle was selected to ensure that the viscosity measurements were collected within the torque limits of the machine. Testing was conducted at 5RPM, with the RV software programmed to collect data points at 30 second intervals. The average viscosity after readings stabilized was used as a test output. Given that asphalt emulsion was tested in this study the specification limits provided in ASTM D4402 for conventional binders were not used, instead the viscosity test was used as a means to check the storage stability of materials.

Recovery Test

Emulsion residue was recovered using the procedure specified in ASTM D 7497 Method B (57,58). Researchers found that this method produces emulsion residue with properties similar to that of RTFO aged binder for regular asphalts (58). It is also reported that Method B which reduces the amount of curing time required is more efficient compared with Method A (57), and more realistic to actual field curing temperatures on pavement surface (59). In Method B curing of emulsion samples is conducted for 6 hours at 60°C and a thin film with thickness of 380 microns is used. After the conditioning the emulsion residue is collected for performance testing.
after cooling. The weight of sample before and after curing is also recorded to calculate the residue asphalt content (RAC) as below:

\[
RAC(\%) = \frac{m_{sample+mat\text{\,after\,curing}} - m_{mat}}{m_{sample+mat\text{\,before\,curing}} - m_{mat}} \times 100\%
\]  

(IV-1)

**PG Testing Using the Dynamic Shear Rheometer**

The Dynamic Shear Rheometer (DSR) (shown in Figure IV-2) is the device used to characterize the viscoelastic property of asphalt binder at intermediate and high temperatures in Superpave Performance Grading (PG) system. To conduct the test, disc-shaped asphalt binder samples are evaluated using a parallel plate testing geometry. The diameter of the plates used is 25 mm and 8mm for high and intermediate temperature evaluation respectively. The plate diameter is adjusted to ensure that the material is tested within the torque limits of the DSR. Tests are conducted in an oscillatory mode of loading at the frequency and level of strain specified for a given performance property. Testing outputs are the complex modulus (G*) and phase angle (δ). These parameters are calculated by the software in the machine based on the torque required to maintain the specified frequency, the time lag between loading and material response, and factors related to the testing geometry. In the Superpave grading system for conventional binders DSR testing is conducted on unaged, RTFO (short-term aged) and PAV (long-term aged) samples. The PG tests used in this study including sample status and parameters limits are presented in Table IV-1.
Table IV-1 Summary of Superpave PG Test Used in this Study

<table>
<thead>
<tr>
<th>Tests</th>
<th>Status</th>
<th>Parameters</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG-High Temperature</td>
<td>RTFO Aged</td>
<td>G*/sin(\delta)</td>
<td>Minimum 2.2 kPa</td>
</tr>
<tr>
<td>PG-Intermediate Temperature</td>
<td>PAV Aged</td>
<td>G*sin(\delta)</td>
<td>Maximum 5000 kPa</td>
</tr>
<tr>
<td>PG-Low Temperature</td>
<td>PAV Aged</td>
<td>Stiffness &amp; m-value</td>
<td>Maximum of stiffness 300 MPa; Minimum of m-value 0.3</td>
</tr>
</tbody>
</table>

**Figure IV-2 Dynamic Shear Rheometer**

**PG Testing – High Temperature**

AASHTO T315 specifies the testing procedure for determining rheological properties of asphalt binder by using DSR (60). To evaluate the high temperature property and prevent rutting damage for asphalt binder, the parameter G*/sin\(\delta\) is used. To resist rutting it is desired to have a high value of G*/sin\(\delta\). Therefore Superpave specifications require minimum values of G*/sin\(\delta\) at the climatic high pavement surface temperature. For hot applied asphalts the test is conducted on both un-aged and RTFO aged asphalt binder samples (61).
In this study the PG system was applied to characterize emulsion residues. Due to the aging that occurs during the residue recovery process, performance was evaluated based on specification criteria for short-term (RTFO) aged binder. This assumption was validated in recent research that found emulsion residues recovered with ASTM D7497 and the RTFO aged base asphalt had similar performance properties (62). In accordance with AASHTO T315 for short term aged binder testing was conducted using the 25 mm plate at a frequency of 10 rad/s, a strain level of 10%, and temperatures ranging from 52°C to 70°C. The $G*/\sin\delta$ vs. temperature relationship was sued to determine the continuous grade of the asphalt binder, where the continuous grade corresponds to the temperature that corresponds to the 2.2 kPa minimum value of $G*/\sin\delta$ as shown in Table III-1. Given application of emulsion to CMA, use of Superpave grading limits are appropriate as it is assumed that the while in-service HMA and CMA experience similar distresses.

**PG Testing - Intermediate Temperature**

The Superpave PG system requires evaluating intermediate temperature performance on long term aged binders to evaluate resistance to fatigue cracking. Long term aging of emulsions residues was conducted in pressure aging vessel (PAV), according to Superpave specifications, this device simulates 8-10 years aging in the field. The Superpave fatigue parameter is $G*\sin\delta$, to prevent fatigue cracking a maximum value of 5000 kPa is specified shown in Table IV-1. The test is conducted on a sample of 2mm in thickness using the 8mm parallel plate geometry at a frequency of 10 rad/s and strain of 1%. The test was conducted at temperatures of 16°C-25°C and the continuous grade was determined based on the maximum specification limit.

**Frequency Sweep Test - Low Temperature**

The Superpave PG grading system uses Bending Bean Rheometer (BBR) test to determine the low temperature performance properties of asphalt binders based on stiffness and relaxation
(m-value) after 60s loading. However in practice, direct measurement of BBR on emulsion residue is difficult to perform due to the small amount of recovered residue available relative to the size of the beams and the need to minimize heating of the samples (58). Research shows that the low temperature property parameters can be estimated from intermediate temperature property through the inter-conversion method by using Frequency Sweep test in DSR (58). In the procedure the parameters (G* and δ) are obtained using a frequency sweep test at temperature of 5°C, 10°C and 15°C. Results are used to construct the master-curve to represent binder stiffness over a wide range of frequency. The frequency of shear testing that corresponds to loading in flexure for 60s at the BBR test temperature is used to convert measurements of G* and δ to the BBR parameters S(60) and m(60) using published equations (58). Research has verified that estimates of BBR properties using Frequency Sweep test conducted in DSR correlates BBR test results well and thus serves as an effective test method to predict low temperature property of asphalt binder (62). Based on these findings the frequency sweep and inter-conversion procedure was adopted in this study.

2. Coating Test

2.1 Materials

As previously stated, achieving sufficient aggregate coating during mixing is required to prevent moisture susceptibility of CMA. More complete aggregate coating is expected to help limit moisture susceptibility of CMA by reducing the amount of water that is absorbed into exposed aggregate. Therefore in this study a simple coating test using digital image analysis method was developed to quantify aggregate coating and check charge compatibility for CMA when selecting materials.

Table IV-2 presents the coating experimental matrix which is developed to isolate the most significant factors affecting aggregate coating, including emulsion-aggregate charge compatibility,
emulsion content, aggregate pre-mixing moisture, and aggregate gradation. In the table, ‘SSD’ represents the saturated surface dry condition. A full factorial was not conducted, instead testing levels, specifically residual asphalt content and aggregate moisture were adjusted based on preliminary results of the experiment.

Table IV-2 Experimental Matrix for Coating Test

<table>
<thead>
<tr>
<th>Factor</th>
<th>Levels</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emulsion</td>
<td>2</td>
<td>Anionic E-150 (proprietary), and Cationic (CSS-1h)</td>
</tr>
<tr>
<td>Residual Asphalt Content</td>
<td>3</td>
<td>3.5%, 4.5%, 5.5%</td>
</tr>
<tr>
<td>Aggregate</td>
<td>2</td>
<td>Limestone/Natural Sand, Granite/Blend Sand</td>
</tr>
<tr>
<td>Gradation</td>
<td>3</td>
<td>Fine, Base, Coarse</td>
</tr>
<tr>
<td>Aggregate Moisture</td>
<td>3</td>
<td>SSD-2%, SSD, SSD+2%</td>
</tr>
<tr>
<td>Mix Schedule</td>
<td>2</td>
<td>Non-agitated, 24 hour agitation</td>
</tr>
</tbody>
</table>

Charge compatibility between the aggregate and emulsion is required to obtain adequate coating and subsequent in-field performance. The aggregate and emulsion sources chosen for this study represent both charge-compatible and charge-incompatible systems to demonstrate this effect on coating. As discussed previously, anionic emulsions carry a negative charge, while cationic emulsions have droplets which carry a positive charge. Aggregates also have a net surface charge: calcareous aggregates such as limestone have a net-positive surface charge, while siliceous aggregates like granite have net-negative surface charge (18). By including these factors the study allows for evaluation of the impact of varying these factors on extent of coating.

The gradations used for this study were selected based on the concepts of aggregate packing and Superpave mix design protocols (63). Aggregate packing concepts were integrated through application of the Bailey method. The ‘Base’ gradation serves as an initial, dense graded blend; the coarse and fine gradations were selected by equally adjusting Bailey’s gradation parameters, which are parameters that predict the aggregate packing based on VMA values. By adjusting gradation parameters in a systematic way, mixtures with expectedly different volumetric properties are created. This was confirmed for the trial gradations in a previous study (3). The
aggregate gradations and corresponding Bailey’s gradation parameters used in this study are presented in Figure IV-3. The gradations were quantified by fitting the gradation curve to a cumulative Weibull distribution as shown in equation below. The two parameters of the Weibull distribution, $\lambda$ and $\kappa$, describe the shape (fineness or coarseness) and the scale (dense or open/gap-graded), respectively. The key in Figure IV-3 shows the gradation followed by these parameters for reference (for example, Fine ($\lambda$, $\kappa$)).

$$P(x) = 1 - e^{-\left(\frac{x}{\lambda}\right)^\kappa}$$

(IV-2)

where, $P(x) =$ Percent finer than sieve $x$

$x =$ Sieve size in millimeters to the 0.45 power,

$\lambda$, $\kappa =$ Curve fit parameters shape and scale, respectively.

Figure IV-3 Gradations used in Coating Test

The three levels of residual asphalt content were selected considering the respective aggregate gradation specific surface area. An average acceptable asphalt film thickness of 8-10
microns (the effective thickness of the residual asphalt binder film on the aggregate particles) was assumed and the Duriez Method (64) was used for determining the optimum residual asphalt binder content in order to satisfy the selected film thickness requirements. The residual asphalt contents for the respective aggregate gradations were averaged for the aggregate sources and are shown in Table IV-3. Since the estimated residual asphalt contents are between approximately 4.5-5%, values of 3.5, 4.5 and 5.5% residual asphalt content were selected to provide reasonable variation in the coating results.

<table>
<thead>
<tr>
<th>Gradation</th>
<th>Calculated Residual Asphalt Content (AC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine</td>
<td>5.0%</td>
</tr>
<tr>
<td>Base</td>
<td>4.9%</td>
</tr>
<tr>
<td>Coarse</td>
<td>4.6%</td>
</tr>
</tbody>
</table>

Table IV-3 Residual Asphalt Content Based on Duriez Method

One environmental benefit of using CMA is that aggregate stockpiles do not need to be fully dry before mixing; therefore the energy consumed during production is reduced. The three levels of aggregate moisture used in this study center around the SSD condition of the aggregate, which is a readily measureable and identifiable aggregate property through ASTM standards (65,66). Since the absorption of the granite aggregate used in this study is very low (less than 2%), only the SSD and the SSD +2% moisture conditions were tested.

As CMA is stockpiled and trucked to the project site (sometimes up to 24 hours after the initial mixing), significant re-mixing, or agitation, is expected. However, literature reports that over-mixing emulsified asphalt mixtures can actually lead to aggregate stripping and loss of coating for some emulsion-aggregate systems (18). As such, the effect of agitation was considered for the mixtures in this study to identify the possibility of stripping due to the over-mixing of CMA systems. To simulate this effect, mixes were placed back into the bucket mixer for an additional 1.5-2 minutes of mechanical mixing 24 hours after the initial mixing process.
2.2 Testing Method

This study utilized image processing software in which images of the mixture are converted to binary images and individual pixels are identified as coated or uncoated based on their intensity. The detailed image analysis procedure was presented in Chapter III using the image processing software ‘iPas’. This method has also been summarized in AASHTO format and submitted to FHWA Mix Expert Task Group (ETG) for consideration.

3. Modified Boiling Test

3.1 Materials

Both coating and bonding are dependent on physical and chemical properties of the individual components of the emulsion-aggregate system. In this study, four different emulsion types are selected and the experimental matrix as shown in Table IV-4 was completed.

Table IV-4 Experimental Matrix for Boiling Test

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emulsion</td>
<td>4</td>
<td>AE-150, CSS-1h, CSS-2 and CSS-1hl</td>
</tr>
<tr>
<td>Residual Asphalt Content</td>
<td>1</td>
<td>4.5%*</td>
</tr>
<tr>
<td>Aggregate</td>
<td>2</td>
<td>Granite and Limestone</td>
</tr>
<tr>
<td>Gradation</td>
<td>2</td>
<td>Base, Single Size (3/8”)</td>
</tr>
<tr>
<td>Aggregate Moisture</td>
<td>1</td>
<td>SSD</td>
</tr>
</tbody>
</table>

* For single size aggregate, 2.0% of residual asphalt content was used throughout to maintain the same film thickness of 8-10 microns as the base gradation mix.

Two of the emulsions used in coating test were maintained in this portion of the study to demonstrate the effect on charge compatibility. CSS-2 with higher viscosity than CSS-1h and a latex modified emulsion CSS-1hl were also included to provide additional points of comparison. Similar to the coating study, both granite and limestone were included to provide charge compatibility and charge incompatibility conditions with different emulsions. The residual asphalt content of 4.5% and “base” gradation are selected from previous Coating Test. In addition to the project gradation, a mix composed of a single aggregate size of (3/8”) was included to
evaluate the effect of aggregate gradation. Aggregate with SSD condition is used to simulate the aggregate moisture condition in the field.

### 3.2 Testing Method

The Boiling test has been well developed and widely used on conventional asphalt mixtures. However, little research has been conducted on the use of the boiling test for characterization of emulsified asphalt mixtures, and no standard test procedure exists for CMA. In this study, the boiling test procedure specified in ASTM D3625 was followed for sample preparation requirements (27). The output of the test was modified to remove subjective evaluation of coating and replace it with the Image Analysis Method described in Chapter III to quantify coating before and after boiling.

![Figure IV-4 Boiling Test apparatus](image)

Loose CMA mixture samples are cured at specific condition (which will be discussed in next chapter) after mixing. After curing, samples were scanned for image analysis to obtain the coating extent before boiling. The boiling test was conducted on a sample of approximately 500g. The sample was placed in the 5000ml-beaker filled with at least 3000ml boiling water. The boiling
test apparatus is presented in Figure IV-4. A steel basket was used in beaker to prevent mixture directly contacting with the bottom of beaker, where the temperature is much higher than boiling point due to the use of a hot plate as a heat source. A large beaker with more capacity was used in this study to eliminate the need for physically stirring the mixture and provide large surface area exposed to water during boiling as recommended by previous research (67). Based on initial testing results, 10 minutes of boiling time (specified in ASTM D3625) is insufficient to cause stripping during boiling, therefore longer boiling time (20 to 60 minutes) was used to identify the stripping after boiling more significantly. After boiling, the stripped asphalt was skimmed from the surface, and the basket with mixture sample was removed from the beaker. The samples were spread on silicone mats (as shown in Figure IV-5) for drying at ambient temperature for 24 hours until dry for scanning. The drying time was selected based on a previous study (3) which indicates that little moisture will be lost after 24 hours curing at ambient temperature. An alternative way to dry the loose mix is to put a fan over loose mix samples for drying to a constant mass (mass repeats within 0.1% for consecutive 15 min determinations as designated in ASTM D2041 for theoretical maximum specific gravity and density of loose asphalt mixtures), which usually takes 2-3 hours depending on the absorption of aggregate. Then the dry samples were scanned again to obtain the coating extent after boiling.

Instead of using visual observation as specified in ASTM D3625, the imaging method was adopted in this study to evaluate coating extent before and after boiling. The Coating Ratio (CR)
was used as an indicator for evaluating moisture susceptibility by boiling test, and defined by the following equation:

\[
CR = \frac{Coating_{\text{After Boiling}}}{Coating_{\text{Before Boiling}}} \times 100\% \quad \text{(IV-3)}
\]

### 4. Binder Bond Strength (BBS) Test

#### 4.1 Materials

The Binder Bond Strength test is a simple test method performed directly on asphalt-aggregate interface to evaluate the bond strength and the effects of moisture damage (8). Procedures for sample preparation and testing are detailed in AASHTO TP-91 (34). This study selected BBS test as a means of comparison to the Modified Boiling test results. The experimental matrix for BBS test is presented as Table IV-5.

<table>
<thead>
<tr>
<th>Table IV-5 Experimental Matrix for BBS Test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Factor</strong></td>
</tr>
<tr>
<td>Asphalt Emulsion/Residue</td>
</tr>
<tr>
<td>Aggregate</td>
</tr>
<tr>
<td>Aggregate Moisture*</td>
</tr>
<tr>
<td>Condition**</td>
</tr>
</tbody>
</table>

* Dry aggregate plate is used for residue, while SSD plate is adopted for emulsion.  
** For emulsion samples applied, only 24hr-40°C as wet condition is tested.

All four types of emulsions tested in boiling test were included in BBS testing to provide direct comparison between the two methods. The BBS test was used on emulsion after two states of curing, partial and fully cured, to assess which condition best relates to the boiling test. No clear guidelines exist in the current AASHTO standard for curing of emulsions, as it is left to the user. In this study, emulsions were cured on the aggregate substrate for 24 hours at 60°C. The fully cured state is represented by testing emulsion residue recovered with Method B described in ASTM D7497. Aggregate mineralogy was held constant throughout the study, as shown by
inclusion of both granite and limestone sources. The aggregate moisture condition was also varied. For emulsions aggregate plates in the SSD condition were used to better represent the field. Use of the SSD condition is not possible for emulsion residues due to the high aggregate application temperature for sample preparation recommended by the AASHTO procedure. Three moisture conditions are used for BBS test, and wet conditions with two extreme conditioning time lengths specified in standard are chosen to study the conditioning time effect on test results. These conditions were selected based on previous research (8).

4.2 Testing Method

AASHTO TP-91 designates the testing methods for both hot asphalt binder and emulsified binder (34). The same testing procedures were followed as the AASHTO standard with minor modifications in sample preparation for this study. The test apparatus is shown in Figure IV-6.

The output of the test is the pull-off tensile strength (POTS) (8), calculated as:

\[
POTS = \frac{(BP \times Ag) - C}{A_{ps}}
\]  

(IV-4)

where \( Ag \) is the contact area of gasket with reaction plate (mm\(^2\)), \( BP \) is the burst pressure (kPa), \( A_{ps} \) is the area of pull stub (mm\(^2\)), and \( C \) is the piston constant.

Figure IV-6 Binder Bond Strength (BBS) Test apparatus (34)
**Test on Emulsion Residue**

The same test procedure as for hot asphalt binder as specified in AASHTO standard was followed for emulsion residues. Recovered residues were collected and prepared for molding the binder samples. Aggregate substrates were cleaned by ultrasonic cleaner, dried and placed at 145°C oven together with pull-out stubs for conditioning for at least 45 minutes to reach the application temperature. Then the stubs were removed from the oven and the binder sample was placed immediately on the stub for approximately 10 seconds, and pressed on the aggregate substrate firmly, as shown in Figure IV-7. Dry-conditioned samples were left at ambient temperature for 24 hours before testing while wet-conditioned samples were kept at ambient condition for 1 hour and then placed in water bath for specified conditioning time. After conditioning, wet-conditioned samples were kept at ambient temperature for one hour to reach the testing temperature prior to testing.

![Figure IV-7 Application of binder on stub and aggregate substrate (34)](image)

**Test on Asphalt Emulsion**

The procedures defined in the AASHTO standard for sample preparation and testing of emulsions was followed in this study. Specifically, aggregate substrates were cleaned and conditioned in distilled water overnight to achieve SSD condition. The silicone molds were placed on SSD substrate and each mold was filled with emulsion of 0.8±0.05 g as shown in Figure IV-8. The whole assembly then was cured in 60±2°C forced draft for 24 hours trying to
reach a “fully cured” state but prevent over-aging. The pullout stubs were heated to 60°C before application. After reaching the application temperature, the substrate was taken from the oven and silicone molds were removed. The stubs were applied immediately on the emulsion samples with firmly pressing. The same conditioning procedure prior to testing as detailed in the previous section was followed for cured emulsions.

![Image](image.png)

**Figure IV-8 Application of emulsion on substrate**

The pull-off test was conducted at ambient temperature for both residue and emulsion with loading rate of 100 psi/sec as specified in standard. The Bonding Ratio (BR), defined as the indicator for evaluating moisture susceptibility of emulsion-aggregate bonding by BBS test, is calculated in a similar fashion as the Coating Ratio (CR) previously defined for the boiling test, shown as below:

\[
BR = \frac{POTS_{\text{Wet}}}{POTS_{\text{Dry}}} \times 100\% \quad \text{(IV-5)}
\]

5. Development of CMA Mix Design

5.1 Materials

To verify the modified boiling test results with mixture performance testing, it is first necessary to establish a mix design procedure for CMA. Two cationic emulsions were selected
and compacted with two different aggregate types to develop a mix design method. Mix design samples were tested for indirect tension strength to obtain the relationship between emulsion content and tensile strength for CMA. The experimental matrix for CMA mix design is listed in Table III-6.

### Table IV-6 Experimental Matrix for CMA Mix Design

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emulsion</td>
<td>2</td>
<td>CSS-1h, CSS-1hl</td>
</tr>
<tr>
<td>Aggregate</td>
<td>2</td>
<td>Granite and Limestone</td>
</tr>
<tr>
<td>Gradation</td>
<td>1</td>
<td>Coarse*</td>
</tr>
<tr>
<td>Aggregate Moisture</td>
<td>1</td>
<td>SSD</td>
</tr>
<tr>
<td>Emulsion Content</td>
<td>4**</td>
<td>Trial-0.75%, Trial***, Trial +0.75%, Trial+1.5%</td>
</tr>
<tr>
<td>Replicates</td>
<td>3</td>
<td>1- G_{mm} and Coating sample, 2- G_{mb} (volumetrics) 3- G_{mb} (volumetrics)</td>
</tr>
</tbody>
</table>

* The “coarse” gradation is selected based on the Superpave gradation limits for surface course with nominal maximum aggregate size (NMAS) of 12.5mm.
**Only 2 extreme limits were used for CSS-1hl.
*** “Trial” is estimated based on surface area calculation and coating test.

The CSS-1h and CSS-1hl emulsions were selected based on results of the coating and boiling test collected during the study. Granite and limestone from the same sources as coating and boiling test were maintained to provide consistency across all test methods. The gradation selected was designed based on the Superpave gradation limit for surface course with nominal maximum aggregate size (NMAS) of 12.5mm. The gradation curve is shown as Figure IV-9. SSD was selected as the pre-mixing aggregate moisture condition to simulate the field condition. As a result, in this study the aggregate moisture content was fixed. Four different emulsion contents were selected to provide a reasonable variation for mix design and to maintain consistency with Superpave mix design procedures. The “Trial” emulsion content was based on surface area calculation and coating test, for these materials the “Trial” is determined as 8%. Three replicates were prepared: one is for coating test verification and G_{mm} measurement, and the other two are for G_{mb} measurement. As a result, both the coating test and volumetric analysis can be conducted using the number of samples selected.
5.2 Testing Method

The purpose of the mix design is to determine the design emulsion content (DEC) in this study. The difficulty in mix design for CMA is that there is currently no guidance regarding if the DEC should be selected on a volumetric basis or performance basis. Also required limits for these properties do not exist. As a result, the following procedures were conducted towards the goal of selecting the final job mix formula: compaction, curing, determination of density, volumetric analysis and indirect tension test.

Compaction

Aggregates were poured into mixing bucket and mixed with pre-mixing water followed by emulsion of specified amount for 1.5-2 minutes by mechanical mixer. The mixtures were transferred into a pan and cured at ambient temperature for 2 hours prior to compaction to simulate the stockpiling and transportation that occurs in the field (similar to the HMA laboratory compaction process).
The perforated mold was used for compaction in this study to allow for removal of water in mixture. Mixtures were poured into the mold and compacted to 100 gyrations using a constant vertical pressure of 600 ± 18 kPa by Superpave Gyratory Compactor (SGC) as shown in Figure IV-10. The 100 gyrations selected is the design compaction effort for a HMA mix designed for medium traffic (10 million ESALs) and exceeds the compaction effort required for mixes rated for lower traffic volumes. The compaction effort (number of gyrations) was also selected to ensure locking point is achieved. During compaction the SGC automatically records specimen height for each gyration, allowing for generation of compaction curves (density vs. gyrations).

![Superpave Gyratory Compactor with perforated mold](image)

**Figure IV-10 Superpave Gyratory Compactor with perforated mold**

**Curing**

After compaction, samples were cured with confining molds at 60°C oven for 72 hours and then left to cool at ambient temperature for another 24 hours. Aluminum perforated confining molds (Figure IV-11) were used to prevent samples from collapsing immediately after compaction and during the early stages of curing. This was done because the emulsion immediately after compaction does not provide adequate strength to maintain the sample geometry, thus a level of confinement is required to allow for further curing and subsequent
evaluation of samples. To evaluate rate of curing, moisture loss by mass was monitored at 24 hour intervals during this curing period.

![Image of CMA mixture samples with confining molds](image)

**Figure IV-11 CMA mixture samples with confining molds**

**Determination of Volumetric Properties $G_{mm}$ and $G_{mb}$**

The same procedure used for HMA compacted mixture for determination of $G_{mm}$ and $G_{mb}$, as specified in ASTM D2041 and D6752, are used in this study for the CMA mixes(68,69). $G_{mm}$ refers to the theoretical maximum specific gravity of uncompacted asphalt mixtures while $G_{mb}$ means bulk specific gravity of compacted asphalt mixtures. The $G_{mm}$ was run on the loose samples after 24 hours curing at ambient temperature. Previous study (3) indicates that little moisture is lost after 24 hours curing at ambient temperature. Therefore 24 hours curing is adequate for density measurement of loose mix. The $G_{mb}$ was run on samples after curing with the same procedure as HMA.

**Volumetric Analysis**

In contrast to HMA, there is potential that after curing CMA samples will contain moisture inside as the aggregate structure developed during compaction prevents moisture from evaporating from the inner portion of the sample. To account for this circumstance in CMA volumetric analysis, two schemes were considered to include the different moisture condition inside the mixture: 1) mixture with asphalt absorbed into aggregate pores, and 2) mixture with free water in the voids. The detailed calculation procedure and equations are listed as follows:
Air voids content: \( VA = 100\left[1 - \left(\frac{G_{mb}}{G_{nm}}\right)\right] \)  

Total asphalt binder content by total mix mass: \( P_b = 100\left(\frac{M_b}{M_{agg} + M_b + M_w}\right) \)  

Total water content by total mix mass: \( P_w = 100\left(\frac{M_w}{M_{agg} + M_b + M_w}\right) \)  

Total aggregate content by total mix mass: \( P_{agg} = 100\left(\frac{M_{agg}}{M_{agg} + M_b + M_w}\right) \)  

Total asphalt binder content by total mix volume: \( VB = \frac{P_b G_{mb}}{G_b} \)  

Assumed absorbed asphalt content by total mix volume:  
\[
AVBA = G_{mb}\left(\frac{P_b}{G_b} + \frac{P_w}{G_{sb}} - \frac{100}{G_{nm}}\right)
\]  

Assumed absorbed asphalt content by total mix volume (AVBA) serves as the key parameter determining which scheme the mixtures belong. If AVBA of the mixtures is above 0, it means they belong to Scheme I where aggregate is below SSD condition and part of asphalt is absorbed; otherwise mixtures belong to Scheme II with free water in voids based on that AVBA is less than 0. The two schemes are described in details as follows.
Scheme I: if $AVBA > 0$

Figure IV-12 Scheme I – below SSD condition

Absorbed asphalt content by total mix volume: $VBA = AVBA$  \hspace{1cm} (IV-12)

Absorbed water content by total mix volume: $VWA = G_{mb} \cdot P_{agg Absorption} - VBA$  \hspace{1cm} (IV-13)

Absorbed water content by total mix mass: $P_{WA} = \frac{VWA}{G_{mb}}$  \hspace{1cm} (IV-14)

Effective asphalt content by total mix volume: $VBE = VB - VBA$  \hspace{1cm} (IV-15)

Voids in the mineral aggregate by total mix volume: $VMA = VA + VBE$  \hspace{1cm} (IV-16)

Voids filled with asphalt: $VFA = 100 \left( \frac{VBE}{VMA} \right)$  \hspace{1cm} (IV-17)
Aggregate specific surface: \( S_s \geq \frac{P_{0.30} + P_{0.15} + P_{0.075}}{S_s} \) \text{ (IV-18)}

Apparent film thickness (\( \mu m \)): \( AFT = \frac{1000VBE}{S_s P_s G_{mb}} \) \text{ (IV-19)}

**Scheme II: if AVBA < 0**

![Diagram](image)

Figure IV-13 Scheme II – equal to or above SSD condition

Absorbed asphalt content by total mix volume: \( VBA = 0 \) \text{ (IV-20)}

Effective asphalt content by total mix volume: \( VBE = VB \) \text{ (IV-21)}

Free water content by total mix volume: \( VFW = G_{mb} \left( 100 \left( \frac{P_b}{G_{mb}} \right) - \left( \frac{P_z}{G_{zb}} \right) \right) \) \text{ (IV-22)}

Voids in the mineral aggregate by total mix volume: \( VMA = VA + VBE + VFW \) \text{ (IV-23)}
Voids filled with asphalt: \( VFA = 100 \left( \frac{VBE}{VMA} \right) \)  

Aggregate specific surface: \( S_s \geq \frac{P_{0.30} + P_{0.15} + P_{0.075}}{5} \)  

Apparent film thickness (μm): \( AFT = \frac{1000VBE}{S_s P_{G_{mb}}} \)

From the above analysis, VMA, VFA and other volumetric parameters were determined for each mixture sample either from Scheme I or II. The major difference between the two sets of equations is the calculation of VMA due to the existing free water in Scheme II.

**Indirect Tension (IDT) Test**

Indirect Tension (IDT) test serves as an effective tool to evaluate the mixture quality and initial assessment of potential for rutting and cracking. IDT test has been widely used by previous researchers in mix design procedures (70, 71, 72). This study adopted the standard IDT test procedure as specified in ASTM Standard D6931 (51). The configuration of the testing equipment is shown in Figure IV-14.

![Indirect Tension test equipment](image-url)
The tensile strength is calculated as follows:

\[ S_t = \frac{2P}{\pi tD} \]  

(IV-27)

where:

- \( S_t \) = tensile strength, psi
- \( P \) = maximum load, lbf
- \( t \) = specimen height before tensile test, in.
- \( D \) = specimen diameter, in.

Once all above procedures for mix design were completed, the design emulsion content (DEC) for further performance tests was determined based on volumetric analysis and IDT results. Considering that the typical air voids observed in the field after 1-2 years service is between 10%-15%, in this study 12% was selected as the target air voids. The target density and maximum indirect tensile strength were combined to determine the design emulsion content.

6. TSR Test

6.1 Materials

The same emulsion CSS-1h and CSS-1hl were used to compare the moisture susceptibility with different aggregate mineralogy by compacted mixture TSR test. The experimental matrix is listed in Table III-7. The design emulsion content (DEC) was determined as described previously. The standard dry and wet conditions are tested as specified in AASHTO T283 (36). During the initial testing of the TSR it was discovered that the standard wet conditioning temperature of 60°C used for HMA is too severe for CMA mixture due to the potential for insufficient curing, and more importantly the higher air void content. Therefore, a second wet condition with lower conditioning temperature but longer conditioning time was also included in the test matrix.
### Table IV-7 Experimental Matrix for TSR Test

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emulsion</td>
<td>2</td>
<td>CSS-1h, CSS-1hl</td>
</tr>
<tr>
<td>Aggregate</td>
<td>2</td>
<td>Granite and Limestone</td>
</tr>
<tr>
<td>Gradation</td>
<td>1</td>
<td>Coarse</td>
</tr>
<tr>
<td>Aggregate Moisture</td>
<td>1</td>
<td>SSD</td>
</tr>
<tr>
<td>Emulsion Content</td>
<td>1</td>
<td>Design Emulsion Content (DEC)</td>
</tr>
<tr>
<td>Condition</td>
<td>3</td>
<td>Dry, Wet (24hr-60°C + 2hr-25°C), Wet (48hr-25°C)</td>
</tr>
</tbody>
</table>

#### 6.2 Testing Method

The AASHTO T283 was followed in this study to evaluate moisture susceptibility based on the tensile strength ratio with minor modifications to account for use of CMA. Modifications include adjusting of the target air void content and use of multiple conditioning times and temperatures. For HMA the standard requires testing of mixes at 7% air voids, for CMA this value could not be reached, so the target air void content was selected based on the results of the mix design experiment previously described. As explained earlier, a modified wet conditioning procedure was included to accommodate the higher voids content and incomplete curing. The general procedure used for TSR testing is summarized as follows:

1. Compacted mixture samples and loose mixture samples were prepared using the procedure detailed in the mix design;
2. Samples were cured for 72 hours at 60°C and cooled at ambient temperature for 24 hours prior to testing;
3. After curing the $G_{mm}$ and $G_{mb}$ were measured and the air voids was verified so that the target air void content selected based on the results of the mix design was met;
4. Wet (moisture conditioned) samples were vacuum saturated for five minutes to a degree of saturation ranging from 70% to 80%, as specified in AASHTO T283;
5. Wet samples were submerged in a water bath at the specified conditioning temperature for specified time.
6. When conditioning was completed, samples were removed and placed in a second water bath at 25°C for 2 hours to achieve testing temperature. Dry (unconditioned) samples were placed in plastic bags and also conditioned in 25°C water bath for 2 hours before testing.

7. All samples were tested for indirect tensile strength with the loading rate of 50 mm/min and the maximum load was measured and tensile strength ratio was computed. Two replicates were tested for each of the dry and conditioned samples. No freeze-thaw testing was conducted.

The tensile strength ratio is calculated as follows:

\[
TSR = \left( \frac{S_{tm}}{S_{td}} \right) \times 100\% \tag{IV-28}
\]

where:

\(TSR\) = tensile strength ratio

\(S_{tm}\) = average tensile strength of the moisture conditioned samples, psi

\(S_{td}\) = average tensile strength of the dry samples, psi
V. Results and Analysis

This chapter presents all testing results obtained from the test methods described in previous chapter including asphalt emulsion and residue properties, coating test, modified boiling test, BBS test, CMA mix design and TSR test results.

1. Asphalt Emulsion and Residue Properties

1.1 Rotational Viscosity

Viscosity of emulsion was tested to check the storage stability and material consistency of emulsions used in this study. Emulsion viscosity measured at 25°C with rotational speed of 5 RPM by Rotational Viscometer at different storage time is presented in Table V-1. Generally, all emulsions are stable within storage time of 8 weeks. As shown in the table, the viscosity of AE-150 is significantly higher than the cationic emulsions. Factors influencing emulsion viscosity include the residual asphalt content and properties of the base binder.

Table V-1 Rotational Viscosity for Emulsions of Different Storage Time

<table>
<thead>
<tr>
<th>Emulsion Type</th>
<th>Viscosity (cP) 0 week</th>
<th>Viscosity (cP) 2 weeks</th>
<th>Viscosity (cP) 4 weeks</th>
<th>Viscosity (cP) 8 weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE-150</td>
<td>710</td>
<td>710</td>
<td>695</td>
<td>675</td>
</tr>
<tr>
<td>CSS-1h</td>
<td>135</td>
<td>135</td>
<td>135</td>
<td>130</td>
</tr>
<tr>
<td>CSS-2</td>
<td>235</td>
<td>230</td>
<td>230</td>
<td>230</td>
</tr>
<tr>
<td>CSS-1hl</td>
<td>230</td>
<td>230</td>
<td>220</td>
<td>220</td>
</tr>
</tbody>
</table>

1.2 Residue Recovery Test Results

After recovery, the emulsion residue content was determined; results are provided in Table V-2. The ranking of emulsions based on residual asphalt content and emulsion viscosity are the same, consistent with the effects of residual asphalt content on increasing viscosity.
Table V-2 Emulsion Residue Content

<table>
<thead>
<tr>
<th>Emulsion Type</th>
<th>Residue Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE-150</td>
<td>64.6%</td>
</tr>
<tr>
<td>CSS-1h</td>
<td>57.2%</td>
</tr>
<tr>
<td>CSS-2</td>
<td>61.7%</td>
</tr>
<tr>
<td>CSS-1hl</td>
<td>61.2%</td>
</tr>
</tbody>
</table>

1.3 PG Testing—High Temperature

The continuous grade or called “true grade” (TG) of emulsion residue at high temperature, intermediate temperature, and low temperature was determined by different tests using DSR. The high temperature TG is shown in Table V-3. A higher continuous grade indicates better performance as the material can adequately resist distress at higher service temperatures. The high temperature grade of AE-150 is lower than cationic emulsions. CSS-1hl is higher than CSS-1h and CSS-2, indicating better high temperature performance.

Table V-3 High Temperature True Grade for Emulsion Residues

<table>
<thead>
<tr>
<th>Emulsion Type</th>
<th>T (°C)</th>
<th>Replicate 1 (kPa)</th>
<th>Replicate 2 (kPa)</th>
<th>AVE (kPa)</th>
<th>TG (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE-150</td>
<td>52</td>
<td>3.53</td>
<td>3.48</td>
<td>3.505</td>
<td>56.1</td>
</tr>
<tr>
<td></td>
<td>58</td>
<td>1.61</td>
<td>1.59</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>CSS-1h</td>
<td>58</td>
<td>5.06</td>
<td>5.01</td>
<td>5.035</td>
<td>64.0</td>
</tr>
<tr>
<td></td>
<td>64</td>
<td>2.2</td>
<td>2.19</td>
<td>2.195</td>
<td></td>
</tr>
<tr>
<td>CSS-2</td>
<td>58</td>
<td>3.41</td>
<td>3.54</td>
<td>3.475</td>
<td>62.0</td>
</tr>
<tr>
<td></td>
<td>64</td>
<td>1.53</td>
<td>1.59</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td>CSS-1hl</td>
<td>64</td>
<td>3.74</td>
<td>3.77</td>
<td>3.755</td>
<td>69.1</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>1.91</td>
<td>1.93</td>
<td>1.92</td>
<td></td>
</tr>
</tbody>
</table>
1.4 PG Testing—Intermediate Temperature

For intermediate temperature grading, a lower continuous grade is desired as it indicates that the material remains flexible enough to resist fatigue induced damage at lower surface temperatures. The testing results and TG for emulsion residues are shown in Table IV-4. The TG for AE-150 at intermediate temperature is significantly lower than cationic emulsions CSS-1h and CSS-2, showing better resistance on fatigue cracking. This is consistent with the high temperature grading results as it indicates that the asphalt residue for the AE-150 is considerably softer. The modified emulsion CSS-1hl also shows good intermediate temperature performance relative to the other two cationic emulsions. The intermediate temperature grading scale is conducted in increments of 3°C, based on this system the cationic emulsions vary by approximately 1 grade.

Table V-4 Intermediate Temperature True Grade for Emulsion Residues

<table>
<thead>
<tr>
<th></th>
<th>T (°C)</th>
<th>Replicate 1 (MPa)</th>
<th>Replicate 2 (MPa)</th>
<th>AVE (MPa)</th>
<th>TG (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE-150</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G* sin@ 22°C</td>
<td>22</td>
<td>2.29</td>
<td>2.38</td>
<td>2.335</td>
<td>16.2</td>
</tr>
<tr>
<td>G* sin@ 19°C</td>
<td>19</td>
<td>3.64</td>
<td>3.79</td>
<td>3.715</td>
<td></td>
</tr>
<tr>
<td>CSS-1h</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G* sin@ 25°C</td>
<td>25</td>
<td>4.03</td>
<td>3.95</td>
<td>3.99</td>
<td>23.5</td>
</tr>
<tr>
<td>G* sin@ 22°C</td>
<td>22</td>
<td>6.02</td>
<td>5.9</td>
<td>5.96</td>
<td></td>
</tr>
<tr>
<td>CSS-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G* sin@ 22°C</td>
<td>22</td>
<td>4.51</td>
<td>4.46</td>
<td>4.485</td>
<td>21.3</td>
</tr>
<tr>
<td>G* sin@ 19°C</td>
<td>19</td>
<td>6.75</td>
<td>6.67</td>
<td>6.71</td>
<td></td>
</tr>
<tr>
<td>CSS-1hl</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G* sin@ 19°C</td>
<td>19</td>
<td>4.31</td>
<td>3.84</td>
<td>4.075</td>
<td>17.3</td>
</tr>
<tr>
<td>G* sin@ 16°C</td>
<td>16</td>
<td>6.06</td>
<td>5.35</td>
<td>5.705</td>
<td></td>
</tr>
</tbody>
</table>

1.5 Frequency Sweep Test—Low Temperature

Frequency sweep test results at intermediate temperatures were converted into continuous grade at low temperature for emulsion residues using the inter-conversion method (58, 62) as previously described. In relation to performance it is desired to have a low (more negative)
continuous grade as it indicates that the material will resist thermal cracking at lower service temperatures. The final results of TG on stiffness (S) and m-value are shown in Table IV-5. Generally CSS-1h has similar TG with CSS-2 and CSS-1hl, while all of them have higher TG than AE-150 by comparing TG on m-values, indicating that AE-150 has better stress relaxation property on low temperature cracking. However, the stiffness TG of AE-150 is higher than all cationic emulsions. In selecting the final performance grade the higher of the continuous grade results between S(60) and m(60) is used as it represents the limiting factor for thermal cracking resistance.

Table V-5 Low Temperature True Grade for Emulsion Residues

<table>
<thead>
<tr>
<th></th>
<th>S = 300 MPa</th>
<th>M = 0.300</th>
<th>AVE (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE-150 TG</td>
<td>-18.70</td>
<td>-17.88</td>
<td>-18.3</td>
</tr>
<tr>
<td>CSS-1h TG</td>
<td>-24.11</td>
<td>-24.17</td>
<td>-24.1</td>
</tr>
<tr>
<td></td>
<td>-18.03</td>
<td>-18.07</td>
<td>-18.1</td>
</tr>
<tr>
<td>CSS-2 TG</td>
<td>-25.33</td>
<td>-25.69</td>
<td>-25.5</td>
</tr>
<tr>
<td></td>
<td>-20.61</td>
<td>-20.35</td>
<td>-20.5</td>
</tr>
<tr>
<td>CSS-1hl TG</td>
<td>-24.05</td>
<td>-24.15</td>
<td>-24.1</td>
</tr>
<tr>
<td></td>
<td>-22.10</td>
<td>-22.05</td>
<td>-22.1</td>
</tr>
</tbody>
</table>

The results of continuous grade and the overall PG grade for each emulsion are summarized in Table V-6.
2. Coating Test Results

2.1 Factors Influencing Aggregate Coating

The coating test matrix presented in previous chapter was completed using three replicates for each factor combination. Analysis of Variance (ANOVA) was conducted at a confidence level of 95% to screen the significant factors affecting coating. A best-subsets regression analysis was then performed and linear regression model was developed based on the best subsets for the whole emulsion-aggregate system.

Data analysis was conducted using statistical analysis software named ‘R-project’ (73). The ANOVA output is shown in Table V-7. Note that in order to check the procedural repeatability for the three replicates, the ‘Replicate’ factor is also added into the analysis. Higher order interaction effects were not included.

Table V-7 ANOVA Table for Coating Test

<table>
<thead>
<tr>
<th></th>
<th>Df</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emulsion</td>
<td>1</td>
<td>2098.5</td>
<td>&lt;2.2E-16</td>
<td>***</td>
</tr>
<tr>
<td>Aggregate</td>
<td>1</td>
<td>5.2</td>
<td>0.0234</td>
<td>*</td>
</tr>
<tr>
<td>Gradation</td>
<td>2</td>
<td>39.6</td>
<td>4.013E-16</td>
<td>***</td>
</tr>
<tr>
<td>Pre-mix moisture</td>
<td>2</td>
<td>2.0</td>
<td>0.1374</td>
<td></td>
</tr>
<tr>
<td>Agitation</td>
<td>1</td>
<td>9.7</td>
<td>0.0021</td>
<td>**</td>
</tr>
<tr>
<td>Residual Asphalt Content</td>
<td>2</td>
<td>102.5</td>
<td>&lt;2.2E-16</td>
<td>***</td>
</tr>
<tr>
<td>Replicate</td>
<td>2</td>
<td>0.8</td>
<td>0.4346</td>
<td></td>
</tr>
</tbody>
</table>

Note: Significance codes—0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1.

Results presented in Table V-7 indicate that emulsion type, aggregate type, aggregate gradation, agitation and residual asphalt content are deemed statistically significant, and review of
F-values shows that emulsion type has the most influence on the aggregate coating as its F-value is much higher than other factors. Specifically, factors that have strong influence on the model, as defined by ANOVA are emulsion type, aggregate gradation and residual asphalt content. Based on this analysis the ability to change coating through adding pre-mix moisture or changing aggregate type is minimal relative to other mix design factors. It is important to note that the replicate factor is not significant throughout the coating test, indicating that the procedure is reliable and coating results are repeatable.

The effects of the levels selected for the most significant factors were analyzed through Tukey’s Test respectively and summarized in Table V-8.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Description</th>
<th>Difference</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emulsion</td>
<td>Cationic-Anionic</td>
<td>47.6</td>
<td>0</td>
</tr>
<tr>
<td>Gradation</td>
<td>Coarse-Base</td>
<td>6</td>
<td>6.8E-6</td>
</tr>
<tr>
<td></td>
<td>Base-Fine</td>
<td>3.7</td>
<td>0.007</td>
</tr>
<tr>
<td>Residual Asphalt Content</td>
<td>5.5%-4.5%</td>
<td>6.6</td>
<td>2.0E-7</td>
</tr>
<tr>
<td></td>
<td>4.5%-3.5%</td>
<td>9.3</td>
<td>0</td>
</tr>
</tbody>
</table>

From the Tukey’s test results, it was found that use of cationic emulsion significantly increased aggregate coating than use of anionic emulsion. It does verify industry practice which tends to use more mixes with cationic emulsions because they are easier to coat the aggregates and less sensitive to changes in materials conditions (18). The Coarse gradation coated the best, followed by Base and Fine, respectively. Increasing the residual asphalt content was also found to increase coating as expected.

2.2 Best Subsets Regression

A best-subsets regression was used to identify factors to include in a prediction model (74). The factors’ levels were first quantified using specific values rather than qualitative labels. For
example, ‘Gradation’ was quantified using the Weibull parameters $\kappa$ and $\lambda$ presented in Figure IV-3 instead of “fine” and “coarse”, while ‘Agitation’ was labeled using +1 for agitation and -1 for no agitation; ‘Emulsion’ was labeled using +1 for cationic and -1 for anionic, and ‘Aggregate’ was labeled using +1 for limestone and -1 for granite. Table V-9 presents the results of the analysis with the chosen subset outline by statistical analysis software “Minitab”. The subset was chosen based on a combination of a relatively high adjusted coefficient of determination $R^2_{\text{adj}}$ value, and a small Mallows’ Cp value close to the number of variables in the chosen subset (74). Also, a parsimonious model with fewer variables is preferred when selecting the best subset (74). Higher order interaction effects were not considered as interpretation of such factors is difficult for this research, and including interaction factors did not significantly strengthen (in terms of $R^2_{\text{adj}}$) the regression models. Based on Table V-9, the factors selected by best subset are congruent with the ANOVA table showing the most significant factors.

**Table V-9 Factors Selection by Best Subset Regression**

<table>
<thead>
<tr>
<th>Variables</th>
<th>$R^2_{\text{adj}}$</th>
<th>Mallows’ Cp</th>
<th>Emulsion</th>
<th>Aggregate</th>
<th>Gradation, $\kappa$</th>
<th>Gradation, $\lambda$</th>
<th>Aggregate Moisture Content</th>
<th>Agitation</th>
<th>Residual Asphalt Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>76.8</td>
<td>313.1</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>84.5</td>
<td>98.5</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>88.0</td>
<td>2.5</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>88.0</td>
<td>2.8</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>88.0</td>
<td>4.3</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>6</td>
<td>87.9</td>
<td>6.0</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>7</td>
<td>87.9</td>
<td>6.3</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>
Using the subset outlined in Table V-9, a quantitative prediction model is defined as shown in equation below.

\[ Coating = 11.0 + 26.2\text{Emulsion} + 27.6\kappa + 8.74\text{Content}, \quad R^2_{adj} = 88.0\% \]  \hspace{1cm} (V-1)

where,  
- Coating = Estimated percent coated aggregates by total area, %
- Emulsion = +1 when cationic emulsion was used, -1 when anionic emulsion was used
- \( \kappa \) = Gradation scale parameter
- Content = Residual asphalt content by mass, %

It is important to note that the range of applicable values for the parameters included in above equation is limited to the range used in this study (i.e., a value of zero cannot be input into for parameter “Content”).

By changing the mix design factors such as emulsion type, aggregate gradation and residual asphalt content, optimum coating will be obtained by using this model. However since it is impossible to include all kinds of emulsion-aggregate systems by using a universal regression model, practitioners need to run the coating test individually to evaluate the coating extent when different emulsion-aggregate system is used.

3. Modified Boiling Test Results

The Modified Boiling Test was proposed to check coating quality by comparing coating results before and after boiling. Testing conditions for two different aggregate gradations were proposed respectively and Modified Boiling Test was then conducted using the determined testing conditions.

3.1 Determination of Testing Conditions for Base Gradation Aggregate

As part of the development of the procedure, the proper curing condition for CMA loose mix prior to using the boiling test was evaluated. A small study was designed that included one
emulsion (CSS-1h) and two aggregate types (limestone and granite). The materials combinations were subjected to the following curing conditions:

1. Curing for 6 hours at 60°C oven;
2. Curing for 24 hours at 60°C oven;
3. Curing for 72 hours at 60°C oven.

The overall goal of further development of the boiling test is to assess potential for moisture susceptibility of fully cured in-service CMA mixtures. Therefore, the most appropriate curing condition that meets these practical requirements needs to be determined. To further develop the test procedure, boiling times of 20 minutes and 60 minutes were performed to identify the effect of boiling time on extent of stripping.

First, to evaluate rate of curing, both limestone and granite samples mixed with CSS-1h were cured at 60°C oven for 72 hours with moisture loss measured at the increments provided previously, results are shown in Figure V-1. Results indicate that a majority of the moisture is evaporated after the first 6 hours regardless of the aggregate type used. Initially, the limestone lost a bit more water due to the higher absorption of the aggregate relative to the granite.

Figure V-1 Moisture loss within 72 hours curing at 60°C oven
The results of Coating Ratio (CR) for all curing conditions and boiling times are shown in Figure V-2. CR values of CSS-1h mixes for 24-hour cured mixes are higher than 6-hour cured mixes especially for granite, indicating that significant improvements of the quality of the bond at the asphalt aggregate interface occur after a majority of the moisture evaporation is complete. This affect could be attributed to the presence of emulsifiers within the emulsion residues (22). However by comparing 24-hour cured and 72-hour cured samples, the CR doesn’t change significantly for both aggregates.

![Figure V-2 Effect of curing time and boiling time on Coating Ratio](image)

**Figure V-2 Effect of curing time and boiling time on Coating Ratio**

The 20 minutes and 60 minutes boiling results have no significant difference for both aggregate types. Therefore, 24 hours at 60°C oven curing and boiling time of 20 minutes are selected for Modified Boiling Test on base gradation aggregate.

### 3.2 Modified Boiling Test Results for Base Gradation Aggregate

Based on selected curing condition of 24 hours at 60°C oven and boiling time of 20 minutes, the test results are shown in Figure V-3. Based on observation of mixture after curing, it is found that even after the accelerated curing procedures previously established, the AE-150 was not fully cured well as shown by its appearance and tackiness of the mixture when touched. In contrast, the mixtures prepared with different emulsions are fully cured and not tacky when touched. Since
adhesive bond is not totally formed because of inadequate curing, stripping and recoating phenomenon could happen, which explains the increase of the coating after boiling for the AE-150 emulsion.

![Figure V-3 Modified Boiling Test results for base gradation aggregate](image)

**Figure V-3 Modified Boiling Test results for base gradation aggregate**

Both CSS-1h and CSS-2 shows similar trend on different aggregates: limestone has better moisture susceptibility than granite; even though the granite was found to achieve 100% coating, while limestone was coated a less. Therefore higher extent of coating doesn’t necessarily imply improved moisture resistance (quality of coating), justifying the need for test methods capable of evaluating both coating extent and quality. CSS-1hl with no significant difference between aggregate types performs better than both CSS-2 and CSS-1h, indicating the best moisture resistance. However for testing results on base gradation aggregate, all CRs are close to each other and the differences are relatively small. Therefore, the boiling test on single size aggregate was performed to obtain better differentiation as discussed below.

### 3.3 Determination of Testing Conditions for Single Size Aggregate

For use of single sized aggregate the sensitivity to boiling time and curing condition was assessed to determine optimum experimental conditions. Three curing conditions and two boiling time adopted for base gradation aggregate were still used to select the most appropriate testing
condition. CSS-1h and both aggregate types were maintained. The testing results are shown in Figure V-4.

**Figure V-4 Determination of curing condition and boiling time**

By comparing the three curing conditions it can be seen that very little change occurred after 6 hours curing at 60°C and even less after 24 hours curing. Meanwhile, 60 minutes boiling shows significantly decrease in CR relative to 20 minutes boiling, which is different from base gradation aggregate. Therefore to differentiate results more easily, 24 hours curing and 60 minutes boiling were selected for single size aggregate boiling test. This was also done to maintain consistency with the conditions used for the full aggregate gradation.

### 3.4 Modified Boiling Test Results for Single Size Aggregate

The boiling test results for single size aggregate are shown in Figure V-5. CSS-1hl shows the best moisture resistance for both limestone and granite, and CSS-2 performs better than CSS-1h. Related to aggregate types, limestone shows better moisture resistance than granite for both CSS-1h and CSS-2; however granite performs better combined with CSS-1hl. AE-150 was not included due to its poor curing property.
The Modified Boiling Test results for single size aggregate using Image Analysis Method was also verified with the visual inspection method developed by Cuciniello (75) as shown in Figure V-5. Coating Index (CI) is an index indicating coating after boiling similar as CR used in this study. From the figure it can be seen both CR and CI has the same trend among all aggregate-emulsion systems, indicating effectiveness of using imaging method in quantifying boiling test.

**Figure V-5 Modified Boiling Test results for single size aggregate**

4. **BBS Test Results**

BBS test was conducted on both residues and emulsion; both materials were subjected to two combinations of curing time and temperature to assess continued degradation of the bond with prolonged presence in moisture. Results were analyzed to assess the effects of emulsion and aggregate type and also compared to results of the Modified Boiling Test.

4.1 **Test Results on Residues**

The BBS test results on emulsion residues are presented in Table V-10 and Figure V-6.
From Table V-10 it is seen that even with standard recovery procedure (Method B), the AE-150 still hasn’t been fully cured, which leads to relative small POTS values. For limestone, the POTS decreases with conditioning time; however for granite, the POTS doesn’t decrease significantly and even increases a little under 96hr-40°C condition. Based on relatively low values of dry strength the AE-150 emulsion is not deemed appropriate for use with these two aggregate types. Results from Table V-10 also indicate that extended conditioning time does not significantly degrade bond strength relative to 24 hour conditioning as only one combination of emulsion and aggregate (CSS-1h with granite) appears significant.

*For CSS-1hl emulsion, only 96 hour conditioning was performed for both limestone and granite.
By comparing 96 hour conditioning results for three cationic emulsions as shown in Figure V-6, it is seen that dry POTS for limestone has no significant difference with granite for all three emulsions. However limestone is more moisture resistant than granite for CSS-1h and CSS-2 with higher BR values, but ranking reverses for CSS-1hl. By comparing emulsions, it can be seen CSS-1hl performs much better than CSS-1h and CSS-2 no matter for limestone or granite; CSS-1h has higher dry POTS but also increased moisture sensitivity relative to CSS-2.

4.2 Test Results on Emulsions

Test results on emulsions are presented in Table V-11 and Figure V-7. More severe curing problem was seen for AE-150 with very small POTS values as shown in Figure V-7. Almost the same trends with residue test are seen here. Limestone performs better than granite for both CSS-
1h and CSS-2, and CSS-2 is more moisture resistant than CSS-1h. However, dry POTS for all emulsion are much lower relative results on residues, indicating insufficient curing still exists. Therefore, BBS test on emulsion residues are more recommended which is closer to the “fully cured” field condition of emulsion. Due to this reason, CSS-1hl was not included for further comparison.

<table>
<thead>
<tr>
<th>Aggregate</th>
<th>Emulsion</th>
<th>Condition</th>
<th>POTS</th>
<th>BLR</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMS</td>
<td>AE-150</td>
<td>Dry</td>
<td>21.9</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24hr-40°C</td>
<td>13.1</td>
<td>40.2%</td>
</tr>
<tr>
<td></td>
<td>CSS-1h</td>
<td>Dry</td>
<td>255.6</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24hr-40°C</td>
<td>148.7</td>
<td>41.8%</td>
</tr>
<tr>
<td></td>
<td>CSS-2</td>
<td>Dry</td>
<td>206.8</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24hr-40°C</td>
<td>133.9</td>
<td>35.3%</td>
</tr>
<tr>
<td>GN</td>
<td>AE-150</td>
<td>Dry</td>
<td>4.4</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24hr-40°C</td>
<td>0.0</td>
<td>99.0%</td>
</tr>
<tr>
<td></td>
<td>CSS-1h</td>
<td>Dry</td>
<td>235.3</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24hr-40°C</td>
<td>127.7</td>
<td>45.7%</td>
</tr>
<tr>
<td></td>
<td>CSS-2</td>
<td>Dry</td>
<td>198.1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24hr-40°C</td>
<td>125.2</td>
<td>36.8%</td>
</tr>
</tbody>
</table>

**Figure V-7 Comparison of BBS test results on emulsions**

Overall, the results of BBS on both residue and emulsion show the same trend on effects of emulsion types and aggregates mineralogy, which is consistent with the results from Modified Boiling Test.
5. CMA Mix Design

Comparison to mixture moisture damage as measured by the TSR test was conducted to verify observed trends in the boiling test and BBS test. Prior to evaluating performance it was first necessary to establish a mix design procedure to ensure consistent sample preparation for this study. The outcome of the procedure is selection of a design emulsion content based on volumetric analysis and performance testing. Samples were then prepared at the design emulsion content to evaluate the effects of emulsion type and aggregate mineralogy on CMA moisture susceptibility. Analysis of compaction, curing and volumetric will be focused on CSS-1h emulsion only with both of limestone and granite; and subsequently the air voids, ITS will also be discussed towards selecting DEC with limited data for both CSS-1h and CSS-1hl emulsion. The results are presented as follows.

5.1 Compaction

Compaction was constructed as the relationship between density (%$G_{mm}$) vs. compactive effort (Gyrations) for both aggregate types and range of emulsion contents. Results are presented in Figure V-8. Granite demonstrates more sensitivity to changes in emulsion content relative to limestone, due to the lower total liquids content in the granite mixes. By design, the experiment held aggregate moisture content constant at the SSD condition, based on differences in absorption between the aggregate types. This condition resulted in significantly more moisture present in the limestone mix. This behavior is similar to HMA which shows at higher binder contents the change in density is much lower as sufficient material is available to lubricate the mix during compaction. In CMA both the emulsion and water in aggregate serve as lubricants during compaction, thus in the limestone mix there is sufficient water to provide lubrication at lower emulsion contents.
Figure V-8 Comparison of compaction curves for CSS-1h mix

Compaction curves were used to determine the locking points for all combinations based on the definition provided in Chapter II, and the results are provided in Table V-12. The locking points of all compactions are below 100 gyrations, indicating that all compactions have achieved the locking point. Furthermore, locking point for all mixes is in a range of 10 gyrations, indicating that all demonstrate similar behavior. Based on the criteria established for HMA provided in Chapter II, all values of locking point are well above 70, indicating a mix that is “harsh” or difficult to compact. The relative insensitivity of locking point to emulsified asphalt content indicates that the only way to improve workability (reduce locking point) is to change gradation.

Table V-12 Locking Point during Compaction for CSS-1h mix

<table>
<thead>
<tr>
<th>Aggregate</th>
<th>Emulsion Content</th>
<th>Locking Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone</td>
<td>7.25%</td>
<td>96</td>
</tr>
<tr>
<td></td>
<td>8.00%</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td>8.75%</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>9.50%</td>
<td>88</td>
</tr>
<tr>
<td>Granite</td>
<td>7.25%</td>
<td>96</td>
</tr>
<tr>
<td></td>
<td>8.00%</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>8.75%</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>9.50%</td>
<td>85</td>
</tr>
</tbody>
</table>
5.2 Curing

During curing, moisture loss was monitored at 24 hour increments. The moisture losses vs. time curves are provided in Figure V-9. A majority of the moisture was lost during the first 24 hours and all mixes follow similar trends regardless of aggregate type or emulsion content. After three days curing, moisture loss of both groups reduced to less than 0.5%.

![Figure V-9 Moisture loss during curing for CSS-1h mix](image)

Samples dimensions were also monitored before and after curing. Two mechanisms may exist and work simultaneously to cause change in dimensions: 1) shrinkage due to the moisture loss and decreasing of air voids 2) thermal expansion due to heating as curing is conducted at elevated temperatures. The results of all samples dimensions change are shown in Table V-13. As shown, the samples expanded in both height and diameter, with the amount of expansion slightly related to emulsified asphalt content. However, these changes in dimensions were insignificant as all were less than 1mm thus no correction is needed to sample dimensions during the volumetric analysis to account for the curing effect.
Table V-13 Samples Dimensions Change after Curing for CSS-1h Mix

<table>
<thead>
<tr>
<th>Aggregate</th>
<th>Emulsion Content</th>
<th>Expansion in Height (mm)</th>
<th>Expansion in Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.25%</td>
<td>0.4</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>8.00%</td>
<td>0.4</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>8.75%</td>
<td>0.8</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>9.50%</td>
<td>0.8</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Granite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.25%</td>
<td>0.2</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>8.00%</td>
<td>0.5</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>8.75%</td>
<td>0.4</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>9.50%</td>
<td>0.7</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>

5.3 Volumetric Analysis

The volumetric analysis was conducted after measuring the densities ($G_{mm}$ and $G_{mb}$). The calculation procedure was followed as equations shown in Chapter III. The major results are listed in Table V-14.

Table V-14 Volumetric Analysis for CSS-1h Mix

<table>
<thead>
<tr>
<th>Aggregate</th>
<th>Emulsion Content</th>
<th>Gmm</th>
<th>Gmb</th>
<th>Air Voids</th>
<th>AVBA</th>
<th>VMA</th>
<th>VFA</th>
<th>Ss</th>
<th>AFT (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.25%</td>
<td>2.630</td>
<td>2.345</td>
<td>10.8%</td>
<td>3.6%</td>
<td>17.2%</td>
<td>37.0%</td>
<td>3.61</td>
<td>7.85</td>
<td></td>
</tr>
<tr>
<td>8.00%</td>
<td>2.603</td>
<td>2.357</td>
<td>9.5%</td>
<td>3.2%</td>
<td>17.2%</td>
<td>45.2%</td>
<td>3.61</td>
<td>9.63</td>
<td></td>
</tr>
<tr>
<td>8.75%</td>
<td>2.576</td>
<td>2.364</td>
<td>8.2%</td>
<td>2.8%</td>
<td>17.6%</td>
<td>53.0%</td>
<td>3.61</td>
<td>11.55</td>
<td></td>
</tr>
<tr>
<td>9.50%</td>
<td>2.549</td>
<td>2.371</td>
<td>7.0%</td>
<td>2.3%</td>
<td>17.9%</td>
<td>60.9%</td>
<td>3.61</td>
<td>13.55</td>
<td></td>
</tr>
<tr>
<td>Granite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.25%</td>
<td>2.500</td>
<td>2.218</td>
<td>11.3%</td>
<td>-1.6%</td>
<td>20.9%</td>
<td>38.8%</td>
<td>3.61</td>
<td>10.73</td>
<td></td>
</tr>
<tr>
<td>8.00%</td>
<td>2.477</td>
<td>2.257</td>
<td>8.9%</td>
<td>-2.1%</td>
<td>20.1%</td>
<td>45.4%</td>
<td>3.61</td>
<td>11.94</td>
<td></td>
</tr>
<tr>
<td>8.75%</td>
<td>2.437</td>
<td>2.285</td>
<td>6.2%</td>
<td>-3.8%</td>
<td>20.1%</td>
<td>50.0%</td>
<td>3.61</td>
<td>13.16</td>
<td></td>
</tr>
<tr>
<td>9.50%</td>
<td>2.393</td>
<td>2.289</td>
<td>4.3%</td>
<td>-5.9%</td>
<td>21.1%</td>
<td>51.7%</td>
<td>3.61</td>
<td>14.41</td>
<td></td>
</tr>
</tbody>
</table>

Assumed absorbed asphalt content by total mix volume (AVBA) serves as the key parameter determining which scheme the mixture sample belongs as discuss previously. From the above table, the AVBA of limestone samples are all above 0, which means they belong to Scheme I where aggregate is below SSD condition and part of asphalt is absorbed. Granite samples belong to Scheme II based on the fact that AVBA is less than 0. Volumetric parameters are also presented in Figure V-10 for comparison.
Figure V-10 (a)-(c) Comparison of volumetric parameters for CSS-1h limestone and granite samples
Results of the air voids vs. asphalt content are consistent with findings in the literature review that CMA mixtures are not capable of meeting the air void levels currently used in HMA mix design. As a point of reference the HMA design air voids is 4%, while results from CMA range from 4% - 11% for the mixes tested. Different sensitivity to emulsion content is also observed, specifically at higher emulsion contents as granite shows much lower air void values.

The VMA and VFA values were compared to volumetric targets for conventional HMA as shown in Table V-15. Results for VMA demonstrate little sensitivity to emulsion content, overall VMA of granite is increased by approximately 2% relative to the limestone. Conversely, the VFA parameter is highly sensitive to emulsion content and values of VFA are similar for both aggregate types at most emulsion contents. Comparison of results to Superpave VMA and VFA limits show that VMA is much higher and VFA much lower than what is accepted for HMA indicating that Superpave specification of volumetric parameters is not applicable for CMA. These differences are due to the increased air void levels observed for CMA mixes and the potential for entrapped water at the sample core influencing volumetric properties.

Table V-15 Superpave Specification Limits for VMA and VFA

<table>
<thead>
<tr>
<th>20-yr Traffic Loading (in millions of ESALs)</th>
<th>Minimum VMA (percent)</th>
<th>VFA Range (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.3</td>
<td>15.0</td>
<td>70 – 80</td>
</tr>
<tr>
<td>0.5 to &lt; 3</td>
<td>14.0</td>
<td>65 – 76</td>
</tr>
<tr>
<td>3 to &lt; 10</td>
<td>13.0</td>
<td>65 – 75</td>
</tr>
<tr>
<td>10 to &lt; 30</td>
<td>12.0</td>
<td></td>
</tr>
<tr>
<td>≥ 30</td>
<td>11.0</td>
<td></td>
</tr>
</tbody>
</table>

5.4 Determination of Design Emulsion Content (DEC)

Both CSS-1h and CSS-1hl mixes were included for comparison of air voids and indirect tensile strength in determination of DEC. The air voids and indirect tensile strength (ITS) for both mixes are shown in Figure V-11.
Air voids and ITS for CSS-1h and CSS-1hl mixes

Air voids for CSS-1hl mixes are higher than CSS-1h mixes, but keep decreasing with the increasing emulsion content similar as CSS-1h mixes. It can be clearly seen that ITS also decreases with increasing emulsion content for all combinations of emulsion and aggregate. The emulsion content vs. ITS presented in this study is inconsistent with findings from the literature (70,71,72). In previous work, this relationship was a curve and the emulsion/asphalt content that corresponds to maximum ITS strength was defined as optimum. Based on these results it appears that the factors selected only captured behavior on the “wet side” of the ITS curve.

To check the extent of curing inside the samples, the fracture surface of the IDT tested samples for CSS-1h mixes were checked visually as shown in Figure V-12. Visual observation
indicates that the center of the fracture surface as highlighted in the figure is mostly filled with exposed aggregate. Based on amount of exposed aggregates on the fracture surface of CSS-1h samples through visual evaluation, much more exposed aggregates are observed at higher emulsion contents for both limestone and granite samples, indicating the samples could be insufficiently cured due to the low level of air voids reached at higher emulsion contents.

Figure V-12 Fracture surface of IDT sample

In combination, IDT strength results and analysis of the fracture surface indicate that even though samples prepared at higher emulsion contents result in lower air voids, it does not necessarily lead to improved performance as curing rate is decreased and lower strength values are observed. Based on these results and literature which states that the typical air voids observed in the field after 1-2 years service ranges from 10%-15%, 12% is selected as the target air voids in this study(22,45). The corresponding emulsion contents for all emulsion-aggregate systems were therefore determined as DEC as shown in Table V-16.
Table V-16 Design Emulsion Content for Emulsion-Aggregate Systems

<table>
<thead>
<tr>
<th>System</th>
<th>DEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSS-1h Limestone</td>
<td>7.00%</td>
</tr>
<tr>
<td>CSS-1h Granite</td>
<td>7.00%</td>
</tr>
<tr>
<td>CSS-1hl Limestone</td>
<td>7.25%</td>
</tr>
<tr>
<td>CSS-1hl Granite</td>
<td>9.00%</td>
</tr>
</tbody>
</table>

6. TSR Test Results

Samples were prepared at the DEC prior to testing to verify that the 12±1% limits was met. Results are presented in Table V-17. A total of four replicates were performed for all emulsion-aggregate systems and assigned to two conditioning groups. Results confirmed that all samples met the required air void range, and thus were suitable for performance testing. Then the TSR test was conducted under two conditions: standard condition (24hr-60°C + 2hr-25°C) and modified condition (48hr-25°C).

Table V-17 Verification of Mix Design for CMA

<table>
<thead>
<tr>
<th></th>
<th>Air Voids (%)</th>
<th>AVE (%)</th>
<th>STD</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSS-1h Limestone</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.2</td>
<td>12.3</td>
<td>0.34</td>
<td>2.8%</td>
<td></td>
</tr>
<tr>
<td>12.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSS-1h Granite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.7</td>
<td>11.8</td>
<td>0.10</td>
<td>0.9%</td>
<td></td>
</tr>
<tr>
<td>11.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSS-1hl Limestone</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.9</td>
<td>11.9</td>
<td>0.17</td>
<td>1.4%</td>
<td></td>
</tr>
<tr>
<td>11.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSS-1hl Granite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.4</td>
<td>11.5</td>
<td>0.21</td>
<td>1.8%</td>
<td></td>
</tr>
<tr>
<td>11.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.1 Test Results with Standard Conditioning

TSR results for CSS-1h mixes under standard conditioning (24hr-60°C + 2hr-25°C) are presented in Table V-18. Note that at least two replicates were performed for each condition and only average values are listed in the table.

Table V-18 TSR Results with Standard Conditioning for CSS-1h Mixes

<table>
<thead>
<tr>
<th>Emulsion</th>
<th>Aggregate</th>
<th>Conditioning</th>
<th>Air Voids (%)</th>
<th>Saturation (%)</th>
<th>ITS (psi)</th>
<th>TSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSS-1h Limestone</td>
<td>Wet</td>
<td>12.3</td>
<td>79.5%</td>
<td>12.97</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>CSS-1h Limestone</td>
<td>Dry</td>
<td>12.2</td>
<td>-</td>
<td>99.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSS-1h Granite</td>
<td>Wet</td>
<td>11.7</td>
<td>75.2%</td>
<td>53.20</td>
<td>0.68</td>
<td></td>
</tr>
<tr>
<td>CSS-1h Granite</td>
<td>Dry</td>
<td>11.8</td>
<td>-</td>
<td>78.13</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For standard conditioned wet samples, limestone samples show significant cracks in the water bath during conditioning as shown in Figure V-13. The high moisture damage could be due to the poor curing situation which cannot stand such severe conditioning temperature. The cracked limestone samples were still tested to compare with well-conditioned granite samples. However tests for limestone are considered invalid due to failure during conditioning.

Figure V-13 Conditioning of CSS-1h limestone samples in water bath

6.2 Test Results with Modified Conditioning

Since CSS-1h limestone samples were cracked under standard conditioning, the comparison of TSR for different aggregate mineralogy was not successful. Therefore a modified conditioning
with longer time and lower temperature was used to prevent damage of the samples due to extreme temperature conditions. The testing results for both CSS-1h and CSS-1hl emulsion are shown in Table V-19 and Figure V-14.

<table>
<thead>
<tr>
<th>Emulsion</th>
<th>Aggregate</th>
<th>Conditioning</th>
<th>Air Voids (%)</th>
<th>Saturation (%)</th>
<th>ITS (psi)</th>
<th>TSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSS-1h</td>
<td>Limestone</td>
<td>Wet</td>
<td>11.4</td>
<td>76.8%</td>
<td>36.62</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dry</td>
<td>12.2</td>
<td>-</td>
<td>99.53</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Granite</td>
<td>Wet</td>
<td>11.9</td>
<td>72.6%</td>
<td>21.51</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dry</td>
<td>11.8</td>
<td>-</td>
<td>78.13</td>
<td></td>
</tr>
<tr>
<td>CSS-1hl</td>
<td>Limestone</td>
<td>Wet</td>
<td>11.9</td>
<td>72.0%</td>
<td>44.38</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dry</td>
<td>11.8</td>
<td>-</td>
<td>60.21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Granite</td>
<td>Wet</td>
<td>11.4</td>
<td>72.0%</td>
<td>55.02</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dry</td>
<td>11.2</td>
<td>-</td>
<td>56.79</td>
<td></td>
</tr>
<tr>
<td>CSS-1h (8%) + 1.5% Cement</td>
<td>Granite</td>
<td>Wet</td>
<td>11.6</td>
<td>73.4%</td>
<td>56.78</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dry</td>
<td>11.6</td>
<td>-</td>
<td>70.05</td>
<td></td>
</tr>
<tr>
<td>CSS-1h (8%) + 3.0% Cement</td>
<td>Granite</td>
<td>Wet</td>
<td>11.3</td>
<td>74.1%</td>
<td>83.40</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dry</td>
<td>11.3</td>
<td>-</td>
<td>84.41</td>
<td></td>
</tr>
</tbody>
</table>

**Figure V-14 TSR results using modified conditioning**

After conditioning, no crack or damage was seen for all samples, and IDT test was performed on all samples. From Figure V-14 it can be seen that CSS-1h mixes are not sound in
moisture conditioning with relatively low TSR values. Modified emulsion CSS-1hl mixes significantly improves the TSR values for both aggregate types. Besides, cement was also used in CSS-1h mixes (as shown in Table V-19) to improve their performance, and testing results (provided by Dr. Shaowen Du) show that adding cement also help CMA improve its moisture resistance. Therefore, both modification and addition of cement are capable of improving moisture susceptibility of CMA, and which method to be adopted should be based on economical consideration in the field.

Direct comparison of CMA performance to limits defined for HMA is not possible due to the modified conditioning time used for CMA in this study. As a result the effects of conditioning time/temperature are confounded with possible differences in material performance. Future research is needed to provide a direct comparison between HMA and CMA by maintaining consistent conditioning times and temperatures.

### 6.3 Comparison of CR, BR and TSR

Test results of Modified Boiling Test, BBS test and TSR test are summarized and ranked in Table V-20, where BR with 96hr-40°C conditioning for emulsion residues and TSR with modified conditioning (48hr-25°C) are included for comparison.

**Table V-20 Summary of Test Results of Modified Boiling Test, BBS Test and TSR Test**

<table>
<thead>
<tr>
<th>System</th>
<th>Emulsion</th>
<th>Aggregate</th>
<th>CR Value</th>
<th>CR Ranking</th>
<th>BR Value</th>
<th>BR Ranking</th>
<th>TSR Value</th>
<th>TSR Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSS-1H</td>
<td>Limestone</td>
<td>74.00%</td>
<td>5</td>
<td></td>
<td>53.60%</td>
<td>5</td>
<td>37%</td>
<td>3</td>
</tr>
<tr>
<td>CSS-1H</td>
<td>Granite</td>
<td>70.50%</td>
<td>6</td>
<td></td>
<td>45.80%</td>
<td>6</td>
<td>28%</td>
<td>4</td>
</tr>
<tr>
<td>CSS-2</td>
<td>Limestone</td>
<td>80.70%</td>
<td>3</td>
<td></td>
<td>65.10%</td>
<td>3</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CSS-2</td>
<td>Granite</td>
<td>78.50%</td>
<td>4</td>
<td></td>
<td>55.80%</td>
<td>4</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CSS-1HL</td>
<td>Limestone</td>
<td>89.90%</td>
<td>2</td>
<td></td>
<td>69.80%</td>
<td>2</td>
<td>74%</td>
<td>2</td>
</tr>
<tr>
<td>CSS-1HL</td>
<td>Granite</td>
<td>96.70%</td>
<td>1</td>
<td></td>
<td>97.50%</td>
<td>1</td>
<td>97%</td>
<td>1</td>
</tr>
</tbody>
</table>
All three indices from various tests shows consistent ranking of moisture resistance for different materials. By correlating CR, BR and TSR as shown in Figure V-15, it is seen that very good correlations exist between CR, BR and TSR, indicating the effectiveness of Modified Boiling Test in evaluation moisture susceptibility for CMA.

![Figure V-15 Correlations between CR, BR and TSR](image)
VI. Findings, Conclusions and Recommendations

This chapter summarizes the major findings of this research and draws the final conclusions based on experimental results and analysis. Specific recommendations for future work on this research are also proposed afterwards.

1. Summary of Major Findings and Conclusions

- The Image Analysis Method shows the potential for effective and reliable tool to identify aggregate coating before and after the Boiling Test. In this study the results show low variability of the coating ratio and significant sensitivity to the materials and condition selected.

- Results of the statistical analysis of the aggregate coating for the different emulsion-aggregate systems indicates that emulsion type, aggregate gradation and residual asphalt content are the most important factors that should be considered in mixture design to ensure acceptable coating and resistance to moisture. A prediction model with emulsions and aggregates used in this study is also developed.

- The Boiling Test modified to replace visual inspection with the Image Analysis Method is established as a simple test to evaluate coating quality which can be performed in the lab or in the field. Additional research is needed to further investigate conditions related to loose mix curing prior to conducting the boiling test, as a limited study of curing conditions indicated sensitivity of bonding loss ratio to both curing time and temperature. Results show that after initial curing, the bonding still forms possibly due to the effect of emulsifier and/or aggregate absorption. Curing of 24 hours at 60°C oven is recommended in this study for CMA loose mixture before conducting the Modified Boiling Test. Single size aggregate is preferred instead of whole gradation for better differentiation.
• The mix design method for CMA proposed in this study was evaluated for CSS-1h and CSS-1hl emulsion combined with two different aggregate types. Results demonstrated that achieving lower values of air void content through use of higher emulsion contents is not necessarily beneficial as the low air voids caused significant reduction in the rate of curing of the center of the sample and a corresponding reduction in performance (tensile strength). Therefore 12% was recommended as the target air voids and corresponding emulsion content was selected for the materials used in this study based on volumetric analysis and IDT test as design emulsion content (DEC) for performance test.

• Results of coating ratio from Modified Boiling Test correlates very well with BBS test results for emulsion residues. The coating ratio results also correlate well with TSR test results, indicating that Modified Boiling Test is valid in evaluating moisture susceptibility of CMA as a simple and effective test.

• By using modified emulsion or adding cement, the moisture resistance of CMA is significantly improved.

2. Recommendations for Future Work

While this study represents a significant step forward in mix design and moisture damage evaluation, the CMA technology remains under-developed relative to HMA. The following recommendations are proposed for future consideration and research:

• Further development of the Image Analysis Method used in the coating test and boiling test is recommended to account for fine aggregates and improve repeatability. Use of image analysis is limited by the resolution of the scanner, given the scanner used in this study and those available commercially; the minimum aggregate size that can be identified is 1.18mm. Therefore the current coating procedure is limited to evaluation on the coarse aggregate fraction. Analysis found that results were initially sensitive to differences in sample preparation, thus training related to the procedure detailed in the
AASHTO standard draft is required to maintain consistency in selection of threshold values and sample preparation.

- Even a prediction model with emulsions and aggregates used in this study is developed, however it is still recommended to run coating tests on various combinations of emulsion and aggregate rather than using the prediction model since only limited emulsion types and aggregate sources are included in this study.

- Although initial results are promising related to the ability of tests on component materials (i.e. boiling and BBS) to relate to compacted mixture performance, further research is needed to expand both the emulsion and aggregate types used to conduct this comparison. With a larger data set, correlations between results from Modified Boiling test, BBS test and TSR test could be verified.

- In the BBS test on emulsion, curing of 24 hours at 60°C oven was selected to ensure sample being “fully cured” but prevent over-aging. However results indicate that this condition is inadequate for the emulsion to reach a fully cured state as values of dry bond strength were significantly lower than those collected on emulsion residue. Significant research is needed on defining emulsion curing condition for the BBS test suited for evaluation of CMA.

- AE-150 emulsion can neither lead to satisfactory coating on aggregate nor adequate curing in short term compared with cationic emulsion. Therefore, based on the materials used in this study, cationic emulsion was found more favorable for CMA application in the field.

- Further development of a mix design method is necessary. Including use of a broader range of emulsion contents is required to verify an optimum range of density and performance. Also an expanded study including more emulsion types, aggregate types and gradations are needed to verify the mix design procedure and target air voids.
Furthermore, given an established mix design there is a need to apply advanced performance tests on CMA such as rutting, fatigue and thermal cracking to provide a direct means of comparison to HMA. This work will identify the applications in which CMA is a viable alternative to HMA.
VII. References


45 *Bitumen Emulsions*. USIRF,2008, France.


49 Mike Hemsley Jnr. *Cold Mix Design*. AEMA Annual Conference, Bermuda, 2002


59 Hayner, R. Answering the Call for Performance Through Quality and Mix Design. *AEMA/ARRA/ISSA Annual Meeting*. Bonita Springs, FL, Feb 2012,


75 Cuciniello, G. Developing a Boiling Test to Quantify Effective Bonding of Aggregates with Binder. MS Thesis, the University of Wisconsin-Madison, Madison, WI, 2013.